Impact of Closure Temperature Selection to 3D Thermal Stress Field of Concrete Arch Dam-Applying to SU PAN 1 Dam in Vietnam

Quang Hung Nguyen, Hoang Hung Vu, Van Quan Tran

Abstract: One of the most important issues in the design and construction of concrete arch dam is the selection of appropriate temperature to spray the mortar in order to fill the slots into seamless structures or also known as arch closure temperature. As the temperature in the dam body changes over time, the arch closure temperature also changes over time. When the temperature of the dam points is different from the arch closure temperature, it may cause the movement of the dam to upstream or downstream, causing tensile stress on the upstream or downstream of the dam. Therefore, the arch closure temperature selection has an important decisive significance for the stress field in the dam body. From the practical design of Su Pan concrete gravity-arch dam 1, the selection of appropriate temperature of arch closure for this project in accordance with the current standard of Vietnam is complete. With the actual working conditions of the project as provided, a numerical model is carried on in Ansys. The numerical result shows that the appropriate temperature for the drilling of the deformed slot is 20°C.

Keywords: Concrete arch dam, Closure temperature, Thermal stress field, Appropriate temperature, ANSYS

I. INTRODUCTION

Arch dam is one of the most advanced types of dam in the world with safe and economic effectiveness. On the horizontal section, with its arch in shape, the dam can promote its compressibleness of concrete material. However, in the case of continuous arching, when there is a change in temperature, the stretch of concrete will raise the tensile strength in the arch dam's body. Therefore, when building the arch dam, regularly, the arch dam's structure will be divided into vertical dam segments, until an "appropriate time", grouting will be conducted to fill joints closely in order to create a continuous arch dam. The dam body's temperature at "appropriate time" is called as closure temperature. Because the dam body's temperature varies from time to time, the closure temperature also changes from time to time. When the temperature of all points in the dam is equal to the closure temperature (t_o), the thermal stress will be not produced. When the temperature is higher than the closure temperature (Fig. 1a), the concrete is expansive, the dam will move to the headwater direction. Whereas, when the temperature is lower than the closure temperature (Fig. 1b), the concrete shrink, the dam tends to move the downstream direction. When dam block is restricted by outer or interior restriction, the volume deformation cannot occur freely and thermal creep stress will appear[1-5]. If thermal creep stress is beyond the allowable thermal creep stress of corresponding age of concrete, crack will occur. Therefore, the selection of closure temperature has a significant meaning, it decides the thermal stress field in the dam's body, the stress produced by the temperature is determined through the gap between the temperature at the calculating time and the closure temperature. The article is based on the reality of Su Pan 1 one-way arch dam (Vietnam) to analyze and select a suitable closure temperature.

Fig 1. Tendency to be expanded of the arch dam when the temperature changes

II. THEORY

A. Heat conduction equation

The massive concrete cannot dissipate completely heat by surrounding air therefore its temperature needs to be decreased. Bofang [1] advanced the equivalent equation of heat conduction in mass concrete:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{\partial \theta}{\partial t} \qquad (1)$$

Where:

T: Temperature of concrete (K)

θ_0: Final adiabatic temperature rise of concrete (K)

a: Thermal diffusivity coefficient (m^2/s)

B. Thermal creep stress

Lingfei and Yang [7] presented basic calculation equations (relations 2~5) of thermal creep stress as follows:

$$[K]\{\Delta\delta\} = \{\Delta P_n\}^L + \{\Delta P_n\}^C + \{\Delta P_n\}^T + \{\Delta P_n\}^O \qquad (2)$$

Where:

$\{\Delta P_n\}^L$, $\{\Delta P_n\}^C$, $\{\Delta P_n\}^T$, $\{\Delta P_n\}^0$: Node load increment caused by exterior load, creep of concrete, temperature difference, autogenous volume deformation.

Thermal creep stress increment of each time iterative is:

$$\{\Delta\sigma_n\} = [\overline{D_n}]\left(\{\Delta\varepsilon_n\} - \{\Delta\eta_n\} - \{\Delta\varepsilon_n^T\} - \{\Delta\varepsilon_n^o\} - \{\Delta\varepsilon_n^s\}\right) \qquad (3)$$

$$[\overline{D_n}] = \overline{E_o}[Q]^{-1}, [Q] = \begin{bmatrix} 1 & -\nu & 0 \\ -\nu & 1 & 0 \\ 0 & 0 & 2(1+\nu) \end{bmatrix} \qquad (4)$$

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Quang Hung Nguyen, Thuy Loi, University, Hanoi, Vietnam.
Hoang Hung Vu, Thuy Loi University, Hanoi, Vietnam.
Van Quan Tran, Hydraulic Construction Institute, Hanoi, Vietnam.

Where:

$\{\Delta\varepsilon_n\}$, $\{\Delta\eta_n\}$, $\{\Delta\varepsilon_n^T\}$, $\{\Delta\varepsilon_n^0\}$: Element's strain increment caused by node displacement, by creep of concrete, temperature difference, autogenous volume deformation.

$\overline{E_o}$: Equivalent elasticity module v is poisson's ratio

The final thermal creep stress equals to the sum of all the thermal creep stress increment, that is:

$$\{\sigma_n\}=\{\Delta\sigma_1\}+\{\Delta\sigma_2\}+.....+\{\Delta\sigma_n\}=\sum\{\Delta\sigma_n\} \quad (5)$$

C. Basis to select the closure temperature

1) Temperature history in the arch dam

Temperature history in the arch dam can be divided into two separate periods: executing period and operating period. Fig. 2 shows the temperature history in the typical arch dam.

Stage ①, ② and ③ represent the executing period and stage ④ and ⑤ represent the operating period. The temperature in the Fig. 2 is considered as medium temperature. During the executing period, the dam must subject to changes from the surrounding environment, sun radiation, cement hydration and artificial cooling from cooling pipes. The principal target of analyzing the arch dam's temperature in this period is to: determine the optimal concrete temperature in form and to select time in order to grout expansion joints for arch closing. In the operating period, the concrete arch dam suffers from impacts of the environment (environment temperature and temperature of water reservoir as well as changes of sun radiation).During this period, the dam is considered as a continuous structure, thus, the gap between the dam temperature and the closure temperature can lead to the compressive or tensile stress in the dam body, and this can make the dam to be cracked and affect the dam's stability.

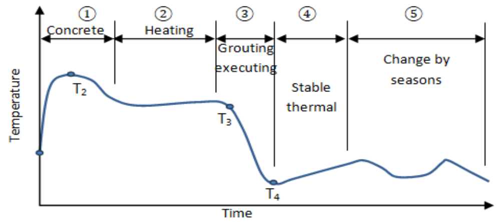

Fig 2. Temperature history of a typical concrete dam

T_1: Temperature of concrete pouring; T_2: Highest temperature after concrete pouring (Stage of temperature increase); T_3: Temperature after free calorification into the environment; T_4: Temperature when grouting expansion joints

D. Standards of stress restriction

(1) Assessment according to standards of the US [8]: poured concrete for 90 days. In which:

f'_c: Compressive strength of 80-day concrete, for cylinder model with 15cm in diameter, 30 cm in height

f'_{cr}: Target concrete compressive strength. $f'_{cr}=f'_c$+600psi

f'_t: Tensile strength of 180-day concrete

f_c: Allowed compressive stress in the dam

f_t: Allowed tensile stress, with the value equal to 10% of compressive stress.

F_S: Slip safety factor

f'_{cd}: Compressive strength for brunt, equal to 130% f'_c

f'_{td}: Compressive strength for brunt, equal to 130% f'_t

f_{cd}: Allowed compressive strength for brunt

f_{td}: Allowed tensile strength for brunt

For actual construction execution in Vietnam, concrete grade is a term used in designing. According to process 22TCN18-79, the basic concepts are as follows:

Cube standard sample: 15×15×15 cm ; Calculated strength of concrete R_{tt} (kG/cm^2), for probability of 0.9986 ; Specified strength R_{tc} (kG/cm^2), for probability of 0.95 ; Concrete grade signed as R, for probability of 0.5 of 28-day concrete.

According to standards of the US:

Cylinder sample with 15cm in diameter, 30cm in height

f'_c: for probability of 0.95

Number of designing day: 90 days

f'_{cr} for probability of 0.5

According to the above basis, if the concrete grade is used as designing norm, f'c will be in proportion to the specified strength (the same probability) after converting from cube sample into cylinder sample.

Strength factor of cube / cylinder ~ 0.83 is used regularly.

Therefore, get a formula converting from f'_c into the concrete grade:

$$[M = 10*(f_c' + 4.14)*1.2] \quad (6)$$

Where:

M: 28-day concrete grade

f'_c: required strength, calculated as MPa

1.2: Factor converting from cube sample into cylinder sample

Table 1. Standard of stress assessment according to standards of the US, static load

Cases to calculate	F_c	F_t	F_S
Usual operation	$f'_c/4$	$f'_t=0.1f'_c$	2.0
Unusual operation	$f'_c/2.5$	$f'_t=0.1f'_c$	1.3
Extreme	$f'_c/1.5$	$f'_t=0.1f'_c$	1.1

Table 2. Standard of stress assessment according to standards of the US, brunt

Cases to calculate	F_{cd}	F_{td}	F_{sd}
Dynamic usual	$f'_{cd}/2.5$	f'_{td}	1.3
Dynamic unusual	$f'_{cd}/1.5$	f'_{td}	1.1

Table 3. Summary of allowed strengths for concrete grades

Concrete grade	f'_{c90} (MPa)	$[f'_c]$ with F_S=4 (MPa)	$[f'_c]$ with F_S=2.5 (MPa)	$[f'_c]$ with FS=1.5 (MPa)	f'_t (MPa)
M100	4.19	1.04	1.68	2.79	0.42
M150	8.36	2.09	3.344	5.57	0.84
M200	12.52	3.13	5.01	8.34	1.25
M250	16.69	4.17	6.68	11.12	1.67
M300	20.86	5.215	8.344	13.9	2.08

(2) Assessment according to Standards of Vietnam

The dam is considered to be ensured the common stability if:

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$$n_c \sigma \le \frac{m}{k}\phi(R_k, R_n) \qquad (7)$$

In which: k: Safety factor; n_c: Factor of load combination; m: Factor of working condition.

R_k and R_n are concrete strength calculated. According to reinforced concrete standard for hydraulic construction, 28-day R_k and R_n for some types of concrete is mentioned as in Table 4.

Table 4. Calculated strength for some types of concrete

Type of concrete	Calculated tensile strength, limit state I (MPa)	Calculated compressiv strength, limit state I (MPa)
M150	0.63	7.00
M200	0.75	9.00
M250	0.88	11.00
M300	1.00	13.50

III. APPLIED TO SUPAN 1 CONCRETE ARCH DAM

A. Introduction of work

Su Pan 1 hydroelectric work is located on Muong Hoa Stream, at a distance of 12 km from SaPa Town, Lao Cai Province toward the Southeast. The work has the following principal parameters:

Elevation of common increase water level as 930m, dead water level as 918m. Elevation of dam top as 932m.
The structure of dam is arch shape with one-way of gravity
Capacity of machine installation: 30MW
Average output in many years Enn=115.27 10^6 kWh
Work level: Level II (According to Decree No.15/2013/NĐ-CP).

B. Structure of the arch dam

The arch dam has one-way gravity with the curved radius of 100m. The dam is located mainly on IIA stone ground, the left shoulder is partly located on IB ground. The dam's top has an elevation of 932m, the lowest bottom of the dam has an elevation of 875m. Therefore, the highest elevation of the dam is 57m.

Central angle is 74^o. Two sides of shoulders have two straight line in tangent with the curved radius.

Spillway is located in the river's bed with 4 spill chambers and lift gate. Each spill chamber is 9.2m in width.

Sand discharge gate is located in the right side of the spillway with 9m in width.

The dam is designed with concrete grade of M150, concrete grade of M200 for the headwater area. Concrete force-resisting pillars for spilling: M250, Concrete curved side for spilling: M300.

The horizontal section of the damp at the location of rolling weir and spillway is shown in Fig. 3.

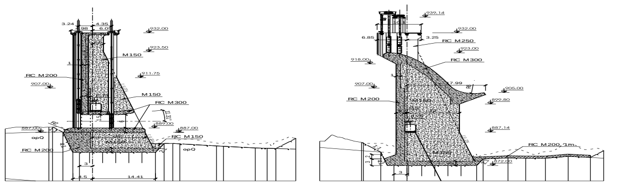

Fig 3. Vertical section at the location of rolling weir and spillway

C. Material properties

A range of thermal and mechanical properties of mass concrete are listed in Table 5.

Table 5. Mechanical properties of the mass concrete

Concrete	M150	M200	M250
G (N/m^3)	2.36E+04	2.36E+04	2.36E+04
E_s (Pa)	2.10E+10	2.40E+10	2.65E+10
μ_s	0.18	0.18	0.18
$f'_{cs}28$ (Pa)	8.36E+06	1.25E+07	1.67E+07
f'_{cs90} (Pa)	1.01E+07	1.49E+07	1.96E+07
E_d (Pa)	1.5*ES	1.5*ES	1.5*ES
μ_d	0.25	0.25	0.25
f'_{cd28} (Pa)	10.87	16.29	21.7
f'_{cd90} (Pa)	13.14	19.32	25.49

Thermal properties of mass concrete:

Specific heat: 750 (J/kg.^{o}C) ; Thermal conductivity: 1.7 (W/m.^{o}C); Convection coefficient concrete - water: 900 (W/m^2 .^{o}C); Convection coefficient concrete - air: 13 (W/m^2 .^{o}C); Coefficient of thermal expansion: 1.2e-5 (1/^{o}C)

The ground parameter collected in accordance with the plate test result is shown in Table 6 .

Table 6. Mechanical properties of the foundation rocks

Soil layer	Modulus of strain E (Pa)	Poisson's ratio	Density (kg/m^3)
IB	3E9	0.32	2700
IIA	8E9	0.27	2700
IIB	1E10	0.27	2700

Thermal properties of foundation rock:

Specific heat: 1050 (J/kg.^{o}C); Thermal conductivity: 2.63 (W/m.^{o}C); Convection coefficient foundation - water: 900 (W/m^2 .^{o}C); Convection coefficient foundation - air: 13 (W/m^2 .^{o}C); Coefficient of thermal expansion: 9E-6 (1/^{o}C)

D. Environmental parameter

(1) Temperature of environment and thermal radiation

The environmental temperature is collected in Sa Pa measurement station. Monthly average temperature and daily temperature designed are shown in Fig. 4. Daily air temperature designed can be converted into cosine representation as below:

$$T_{air}(t) = 15.225 + 6.625\cos(0.986(t-180)) \qquad (8)$$

Because there is no specific Fig 4, the thermal radiation during this stage is added as a part of monthly average temperature, the added value in the winter and summer is 2

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degrees and 4 degrees, respectively.

(2) Water temperature in reservoir

According to Zhu Bofang [9] the water temperature of the reservoir changes in accordance with the depth calculated in the following:

$$T_u(t,y) = T_m(y) + A(y)\cos(\varpi(t - t_o - \xi)) \;; \quad T(t,y) \ge 4^o C \qquad (9)$$

In which:

$$T_{um}(y) = C + (b - C)e^{\frac{-y}{25}}; C = \frac{T_b - bg}{1 - g}; g = e^{-\frac{H}{25}} \qquad (10)$$

$$A(y) = A_o e^{-0.018y}; \xi = 65.4 - 39.42e^{-0.085y}; \omega = \frac{2\pi}{365}$$

y(m) is the water depth; t is time (day); $T_w(t,y)$ is boiling temperature of water at the depth of y in the time of y t; T_b is the water temperature in the bottom of the reservoir; b is yearly average temperature in the reservoir surface; H is the depth of the reservoir; $A(y)$ is yearly thermal amplitude of water at the depth of y; A_o is yearly thermal amplitude in the reservoir surface; t_o is the date with the highest environmental temperature.

In the calculation, only temperature change in accordance with the reservoir's depth is considered, thus, it is calculated according to the following formula:

$$T_u(y) = C + (b - C)e^{\frac{-y}{25}} \qquad (11)$$

With the following parameters in the reservoir: H = 58m; T_b = 33,9^{o}C; b = 10^{o}C. The diagram of water temperature designed in accordance with the depth is provided in Fig. 5.

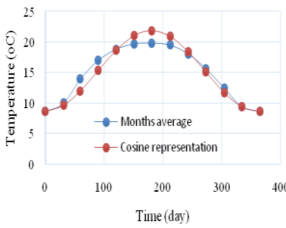

Fig 4. Average air temperature

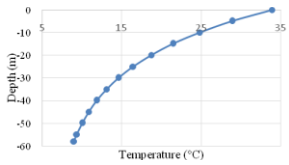

Fig 5. Design water temperature of SuPan 1 Reservoir

(3)Water level in the headwater

The fluctuating water level in the headwater area equivalent to the 1-year cycle according to the hydropower regulation is shown in Fig. 6.

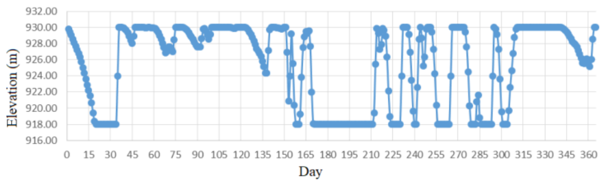

Fig 6. Fluctuating water level in the headwater area

E. Analysis of temperature- stress filed

(1) Calculation model

Calculation model distributing the temperature and the stress of Su Pan 1 arch dam is shown in Fig. 7. In order to consider the impact of the closure temperature on the dam's stressed-strained state, the temperature-structure analysis is used. Firstly, calculate the temperature field, temperature gap that directly produce the temperature stress; secondly, combine with external forces and boundary condition of common stress-deformation analysis problem, the stress field collected will change in accordance with the real-time.

The member net of 3D thermal problem and the stress-deformation analysis is the same. However, the following supposes are applied to accelerate the speed of convergence and problem settlement:

- There is no relative transposition among blocks
- There is no relative transposition between the dam and the ground.

This has no impact on the result of thermal problem, however the convergence speed of the problem will be increased many times.

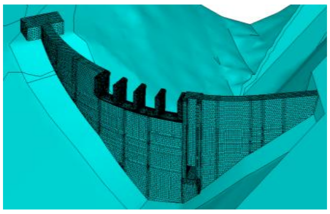

Fig 7: Model of for the temperature-structure calculation

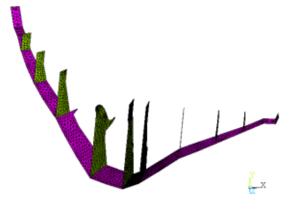

Fig 8. Contact members

Then, the temperature at buttons will be sent in a data file, afterward, it is inserted into the problem of structure analysis. In which: the contact between the dam and the ground is described by the contacting members with the following properties:

- Allowing the relative transposition between concrete and ground with various directions.

- The surface force of friction contact in the tangent direction in accordance with Mohr's theory, as F_{ms}=Sf+C, in which, S is a normal stress on the contacting surface, C is an adherence in the tangent direction, and f is an friction coefficient between two contacting sides.

- There is no adherence in the normal direction.

- The temperature transmitting between two contacting sides depends on the distance of contact between two sides.

Similarly, among blocks, in order to the elasticity of expansion joints, the contact members are used.

Contact members among blocks and between block and ground is shown in Fig. 8.

(2) Method of calculation

The dam is divided into 10 blocks, each block is executed separately, thus, the separate calculation for each block is provided. Then, the result of each block will be generally added in the calculation model of temperature-structure.

Grouting is expected to conduct for thermal joints in the coldest time as in February. Suppose it is executed in the end of February. When determining the closure temperature supposed:

- Grout in February and March, suppose it reaches an elevation of X (m)

- The closure temperature of points below the elevation of X is determined in accordance with the elevation.

- The closure temperature of points above the elevation of X is supposed as the annual average temperature (Grouting will be conducted

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at the end of the year or at the beginning of next year when the temperature decrease).

- Concrete block spreads heat in the air, there is no forced.

(3) Result of calculation

In order to be convenient for the assessment of stress, the safety factor is defined as below:

$$K_{cr} = \frac{[R_{cr}]}{\sigma_3}; K_t = \frac{[R_t]}{\sigma_1} \quad (12)$$

In which:

- K_{cr}: Compressive safety factor; Kt: Tensile safety factor

-[R_{cr}]: Allowed compressive strength, with the consideration of factors in accordance with standards.

- [R_t]: Allowed tensile strength, with the consideration of factors in accordance with standards.

- σ_3 and σ_1 are main compressive stress and main tensile stress, respectively.

The results of calculation for two case of the closure temperature are 15^o and 20^o. With the closure temperature as 20^o, get the results of safety factor in compression and tension ensured. Several locally small locations will be reinforced in the main stress direction

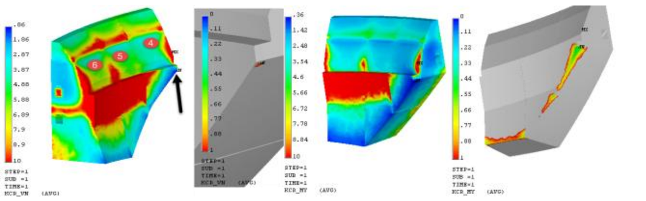

Fig 9: Safety factor in compression according to Vietnamese Standard and American Standards

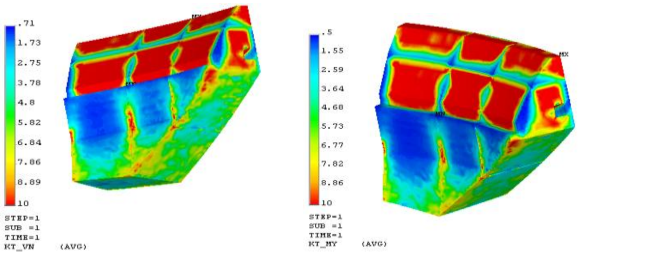

Fig 10. Safety factor in tension according to Vietnamese Standard and American Standards

IV. CONCLUSION

The selection of closure temperature has a significant meaning in affecting the stress field in the dam's body during the executing and operating periods. Basing on the actual design of Su Pan 1 arch dam (Vietnam), the article has clarified the impact of the closure temperature on the dam's stability. With the input conditions provided, the appropriate temperature to grout for expansion joints is 20^o.

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AUTHORS PROFILE

Quang Hung Nguyen was born in 1975 in Hanoi, Viet Nam. I received the Engineering's degree and M.S. degrees in hydraulic construction from the Thuyloi University of Vietnam, in 1997 and 2000 and the PhD. degree in hydraulic structure from Wuhan University, China. Since 1998, he is a lecture in Faculty of Civil Engineering, Thuyloi University and becomes Associate Professor since 2009. From 2007 to 2013, he was Deputy Director of the Institute of Civil Engineering, designed and built many key projects of Vietnam. He is also principal investigator and member of many national science projects as well as Vietnam Ministry of Agriculture and Rural Development. Since 2013, he has been a senior expert in hydraulic construction of Vietnam Ministry of Construction. He is the Advisor of more than 200 bachelors, 40 masters, 2 PhD specialized in hydraulic construction.

Hoang Hung Vu was born in 1978 in Hanoi, graduated from Thuy Loi University, received a Doctorate in Marine Structure Engineering from Hohai University - China, Associate Professor of Thuy Loi University. He teaches hydraulic structures, chairs and participates in many scientific research projects at all levels, verifies many large hydropower projects. Main areas of research are simulation of structure and safety of large concrete dam structures, earthquakes and heat effects on water works, large span valve gates

Van Quan Tran is a researcher of durability of geomaterials at Institute for hydraulic construction-Vietnam academy for water resources. Dr. Tran holds a Ph.D degree from Ecole Centrale de Nantes-France on 2016. During Apr. 2016 due to Mar. 2017, he is the postdoctoral on Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement (Cerema), France. His researches focused on Durability of geomaterials clay, treated soil, concrete, Modelling of hydro-thermo-chemo-mechanical, Hydration mechanisms of cementitious materials, Thermodynamic modeling, Geochemical model of concrete: corrosion

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