Research on the Durability of Composite Pile Made of Ultra-High-Performance and Common Concrete: Finite Element Analysis

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Abstract. The paper is to study the durability of transmission tower foundation using a combination of ultra-high performance concrete (UHPC) and common concrete (NC) in saline-alkali region. The composite pile is made of outer UHPC sleeve and core ordinary concrete. Due to the excellent durability of UHPC, the outer UHPC sleeve can prevent chloride ion and sulfate ion corrosion as well as save cost. Computer research technology was used to construct a corresponding natural environment for artificial simulation, hence accelerate the experimental test of the natural environment. It can more directly and effectively reflect the durability problems of the actual projects. This paper follows the application of classical similarity theorem of UHPC-NC foundation under saline-alkali erosive environment in Gansu, concrete test beams with the same material composition and structural characteristics were poured, an accelerated artificial simulation was designed. Results on the finite element simulation revealed that the outer wrapped ring of UHPC can effectively block the transmission of chloride ions from the external environment to the center of the cross-section. Under the same environment and operation time, the penetration depth of chloride ion in UHPC-NC combined cross-section is much smaller than that in pure normal concrete cross-sections. Therefore, it can be seen that the UHPC-NC combined cross-section can prevent the penetration of chloride ions in a saline-alkali environment, thereby effectively improving the durability of the transmission structure foundation, and hence ensuring the safety and applicability of electricity transmission structure during operation phase.

Keywords. Ultra-high performance reactive powder concrete, composite pile foundation, finite element simulation, durability, chloride ion resistance.

1. Introduction
The electricity transmission tower project of the northwest saline-alkali region is located in an area with highly corrosive saline soil. In the meanwhile, the wet-dry and freeze-thaw interactions are quite noticeable, and the foundation is more susceptible to serious corrosion, causing the pole tower to tilt or even collapse, which seriously affects the safety and normal operation of the transmission line. Following issues exist among anti-corrosion measures of the concrete foundation in saline-alkali regions: the coating protection method, the service life of the coating is less than 10-15 years, it’s difficult to construct, and the following-up maintenance is even more difficult to achieve; there is a large amount of; cathodic protection operation of the external power supply requires a heavy load of maintenance, which is not suitable for large-scale transmission line projects; using high-performance concrete or polymer concrete for the foundation of the electric tower may delay the corrosion to a
certain degree, but its cost is extremely high and can pose pollution issues; the isolation layer uses mainly mortar block or stones, the cathodic protection steel-plate sheath, and polymer concrete have the disadvantages of poor corrosion protection, high construction requirements, large consumables, and limited use of sacrificial anodes system etc. [1-3].

The advent of ultra-high-performance reactive powder concrete (UHPC) provides from surface material aspect a new way of thinking on solving the foundation corrosion issue of power transmission and transformation engineering [4-8]. UHPC is formulated following the principle of maximum bulk density, mainly composed of cement, fine aggregate, silica fume, quartz powder, water reducing agent, steel fiber and water. Its compressive strength is markedly better than the common concrete. A large number of studies have shown that the compressive strength of UHPC is not only related to composition of the material, but also closely related to the maintenance system. When using normal temperature natural curing or steam curing (generally at 90 °C), the compressive strength of UHPC is 100~230 MPa; when it has been pre-pressed after casting and final curing after autoclaving (generally 175-250 °C), its compressive strength can reach 250~400 MPa; when steel grit is used as the fine aggregate, pre-compression molding and high-temperature heat curing (250-400 °C), the compressive strength can reach more than 650 MPa.

Figure 1. Casting process of the UHPC-NC composite pile foundation.

UHPC has high tensile and compressive strength, about five times the common concrete material. Its dense microstructure makes its durability two orders higher than common concrete, and can be used completely as a corrosion-resistant structure. However, the cost of UHPC is extremely high; the economic suitability of using UHPC for the entire foundation system of transmission line towers is low. In fact, the anti-corrosion capacity of the foundation mainly relies on the layer that is directly touching the external environment, not through the internal core area. Meanwhile, UHPC and common concrete both belong to cement-based material with good interface compatibility and easy integration. Based on the prefabricated assembly concept, we propose the UHPC (as an outer layer)-common concrete (NC, internal core) composite pile foundation (process flow is shown in figure 1). It is anticipated that this combination can significantly increase transmission tower foundation’s anti-corrosion capability in saline regions; at the sometime, it can also greatly reduce the initial cost and lifetime maintenance cost, hence has large potential of gaining broad adoption.
2. Principle of Finite Element Simulation

Theoretical research and application of the UHPC component durability are very limited, and anti-corrosion UHPC-NC is ahead of the UHPC research frontier. The corrosion of steel bars in concrete components caused by chloride ion penetration is one of the most common concrete durability problems. Current research on the penetration of chloride ions in concrete is mostly based on tests, but the tests consume a lot of time and budget. Therefore, numerical simulation is another important method for predicting the service life of structures and evaluating the durability of concrete.

ABAQUS is a large-scale general finite element software developed by American SIMULIA company. Compared with other software such as ANSYS and NASTRAN, it can analyze complex elastoplastic mechanical issues, it is especially capable of dealing with highly nonlinear simulation problems.

Take ¼ of an infinite concrete body, sprinkle chloride salts on both sides of x and y, assuming that the coagulation material is an isotropic homogeneous material, chloride ions do not react with concrete, and the intrusion method is mainly diffusion. The origin of the coordinate is set at the corner. At this time, according to the principle of superposition, the two-dimensional diffusion equation is as follows:

$$\frac{\partial C}{\partial t} = D \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right)$$  \hspace{1cm} (1)

In the formula: C is the chloride ion concentration (%, accounting for the ratio of concrete mass); D is an integrated crack parameter, the thickness of the protective layer, and chloride ion coefficients of concrete material characteristics; x, y are the chloride ion coefficient along the x and y direction respectively; t is the diffusion time of chloride ions.

In terms of heat conduction, the two-dimensional transient heat conduction with normal physical properties and without an internal heat source, the simplified equation is as follows:

$$\frac{\partial \phi}{\partial t} = \alpha \left( \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} \right)$$ \hspace{1cm} (2)

where: \( \alpha = \frac{\lambda}{\rho c} \) is thermal diffusivity, which refers to the ratio of the thermal conductivity of the medium to its thermal capacity; t is the temperature of the external temperature field; \( \tau \) is the time for the temperature field to diffuse; x is the distance for the temperature field to diffuse in the x direction.

In summary, it is feasible to use the same principle of chloride ion diffusion equation and heat conduction equation to conduct finite element simulation.

3. Heat Transfer Model

Heat transfer is a physical phenomenon that exists widely. It can be broadly defined as the phenomenon of heat energy transfer caused by temperature difference. The basic heat transfer methods include mainly the following three types: heat conduction, heat radiation, and heat convection. Due to the complexity of temperature conditions, and the different shapes of the structures in reality, it is difficult to obtain satisfactory results through traditional analytical methods. To solve this problem, the finite element method is currently the most widely used reasonable method. For general problems, the differential equation of the transient temperature field is as follows:

$$\rho c \frac{\partial \phi}{\partial t} = \frac{\partial^2 \phi}{\partial x^2} (k_x \frac{\partial \phi}{\partial x}) + \frac{\partial^2 \phi}{\partial y^2} (k_y \frac{\partial \phi}{\partial y}) + \frac{\partial^2 \phi}{\partial z^2} (k_z \frac{\partial \phi}{\partial z}) - Q = 0$$  \hspace{1cm} (3)

The three \( \Gamma \) boundary conditions of this equation are:

$$\phi = \bar{\phi}$$ \hspace{1cm} (4)

$$k_x \frac{\partial \phi}{\partial x} n_x + k_y \frac{\partial \phi}{\partial y} n_y + k_z \frac{\partial \phi}{\partial z} n_z = q$$ \hspace{1cm} (5)
where: \( \rho \) is the density of the material; \( c \) is the specific heat capacity of the material; \( t \) is time; \( k_x, k_y, \) and \( k_z \) are the thermal conductivity coefficients of the material in three directions at three dimensions; \( Q \) is heat source density; \( n_x, n_y, \) and \( n_z \) are the discovery directions of the boundary cosine; \( \phi \) is the initial temperature at the boundary; \( \phi_a \) is the ambient temperature.

The first term in Equation (3) is the amount of heat required for a unit body to heat up, the second, third, and fourth terms are the heat transferred into the unit body in three directions, and the fifth term is the heat generated by the unit body itself. The balanced relationship of these three terms can be seen from the equation. Regarding the three boundary conditions of this differential equation, from equation (4) to equation (6) are the temperature along the boundary of \( \Gamma_1 \), the heat flow on the boundary of \( \Gamma_2 \), and the heat convection on the boundary of \( \Gamma_3 \) respectively. The first boundary condition is a mandatory boundary condition, that is, a fixed boundary condition that must be met; the second and third boundary conditions are the prescribed or given boundary conditions, mainly for the coordinated solution of the system of equations, which are natural boundary conditions. The superimposition of the three boundary conditions is the entire domain \( \Omega \), which constitutes the environmental boundary composition of the unit body.

Equation (3) is a 3-dimensional heat transfer question. If the temperature change in any direction is 0 (the \( Z \) direction is assumed here), the equation degenerates into a two-dimensional heat transfer differential equation, which has the form below:

\[
\rho c \frac{\partial \phi}{\partial t} + k_x \frac{\partial \phi}{\partial x} + k_y \frac{\partial \phi}{\partial y} = -\rho Q = 0
\]  

The equation’s three \( \Gamma \) boundary conditions are:

\[
\phi = \bar{\phi}(\Gamma, t)
\]

\[
k_x \frac{\partial \phi}{\partial x} + k_y \frac{\partial \phi}{\partial y} = q(\Gamma, t)
\]

\[
k_x \frac{\partial \phi}{\partial x} + k_y \frac{\partial \phi}{\partial y} = h(\phi_a - \phi)
\]

In the formula: \( \phi \) is not a function of the \( z \) variable at this time, and the remaining parameters have the same meaning as above.

In short, solving a heat transfer problem can be seen as solving differential equations by given boundary conditions, that is, to find the \( \phi \) function that meets the conditions.

For heat transfer questions, it is generally divided into two heat transfer methods, steady-state heat transfer and transient heat transfer, which can be understood literally: if the final state of the heat transfer needs to be solved, the steady-state heat transfer method can be used. To solve the heat transfer process, the transient heat transfer method can be used, and the solution is as described above. The steady-state heat transfer can be understood as the superimposition of many transient heat transfers. For steady-state heat transfer, the biggest characteristic is that its temperature field is independent of time. According to the form of equivalent integration in the Galerkin solution, the variation principle of the equivalent equation can be established, and the solution can also be obtained through the interpolation function in elasticity, and because the temperature field variable is a scalar, this makes the steady-state heat transfer much simpler than the transient heat transfer.

4. Solving the Solution of Temperature Field by Finite Element Method

The most important thing of the finite element method of temperature field distribution is to determine the analysis principle of UHPC-NC components. For finite element equations of the planar temperature field, the degree of continuous temperature cannot be directly applied in practice, and the
The continuous temperature problem needs to be discretized. The integration area should be divided into several elements and nodes, so that the continuous temperature of the temperature field can be dispersed to the temperature nodes, and finally the temperature of the node is obtained by the differential finite element method.

In temperature field finite element division, triangular or quadrilateral element can be used based on the shape difference of the cross-sections. The triangular element is more practical but the accuracy is slightly worse. Therefore, it is necessary to increase the unit density where the cross-sectional shape is complex and the temperature gradient changes greatly; otherwise, the unit density can be reduced. On the contrary, while quadrilateral element has higher accuracy, its meshing convergence is poor. Therefore, in order to obtain higher accuracy and better converging effect, the phase method of combining triangular elements and quadrilateral elements is usually used in the program analysis of temperature field to draw the grid, which can not only maintain a certain accuracy, but can also ensure program convergence. In the analysis of temperature field of concrete-filled steel tube members, in order to make the calculation method applicable to both plane problems and axisymmetric problems, the plane is divided into triangular elements, as shown in figure 2. The basic unknown variable on each node of the triangular element is temperature T, which is discretely distributed to the three nodes of the element in the finite element, as shown in figure 3.

![Figure 2. Schematic diagram of member.](image1)

![Figure 3. Nodal dispersion of temperature field.](image2)

The basic unknown variable of each node of the triangular element is temperature T. Let T of element e to be a linear function of x and y, namely:

$$T = a_1 + a_2 x + a_3 y$$

where $a_1$, $a_2$, and $a_3$ are constants to be determined, which can be derived from the temperature value at the node.

By substituting the coordinates and temperature of the node into equation (11), it will give:

$$T_i = a_1 + a_2 x_i + a_3 y_i$$

$$T_j = a_1 + a_2 x_j + a_3 y_j$$

$$T_m = a_1 + a_2 x_m + a_3 y_m$$

(12)

The equilibrium equation of the distribution of cross-sectional temperature field is expressed as:

$$[K][T] + [N]\left\{\frac{\partial T}{\partial t}\right\} = \{p\}$$

(13)

where [K] is the temperature matrix; [N] is the variable temperature matrix, which is a coefficient matrix that considers the temperature change with time, and is a unique term in the calculation of unstable temperature fields.
Expand Equation (13) following Crank-Nicolson’s differential format, once finished, we get the following:

\[
\left[ [K] + \frac{2[N]}{\Delta t} \right] [T]_i = \left[ [P]_i + [P]_{i-\Delta t} \right] + \left[ \frac{2[N]}{\Delta t} - [K] \right] [T]_{i-\Delta t}
\]

(14)

The above equation is for calculating the distribution of concrete temperature field, where \([P]_i\) and \([P]_{i-\Delta t}\) are respectively expressed as the right term of the equation at time \(t\) and \(t - \Delta t\). If the boundary consistent initial temperature field \([T]_0\), the temperature field at time \(t\) can be obtained from this formula, and then \(t + \Delta t\) is substituted for \(t\) in the formula as the initial temperature field, and subsequently the temperature field at time \(t + \Delta t\) is obtained. Same as for the others, they can be deduced by analogy, so that the temperature field at each moment of the time interval \(\Delta t\) can be obtained.

5. Finite Element Model Analysis

The finite element model designed in this study is shown in figure 2, where the radius of the entire cross-section is 1000 mm, the diameter of ordinary concrete is 800 mm, and the thickness of the UHPC layer wrapped around the outer ring is 100 mm. The entire cross-section is freely divided by quadrilateral element, and the divided unit size is 10 mm, as shown in figure 3. The connection between the common concrete in the core area and the wrapped UHPC is through Tie binding constraints. This connection method can greatly simplify the calculation and achieve the interaction between the two, which is closer to the actual situation. When setting the Tie constraint, the outer ring of UHPC with greater rigidity is used as the main surface, and the concrete with relatively lower rigidity is used as the secondary surface.

In this simulation, the ions act directly on the surface of the UHPC hoop, so in addition to the material performance settings of the UHPC and the common concrete materials (as shown in figure 4), two heat transfers, heat radiation, and heat conduction must also be set on the surface of the UHPC hoop. The specific operation settings are shown in figure 5. The parameter settings of the associated material and part of the key parameter settings are shown in figures 6 and 7, respectively.

![Create Part](image)

(a) Choice of composition

![Extrusion](image)

(b) Geometric modeling

Figure 4. The establishment of finite element geometric model.
Figure 5. Schematic diagram of element division of the finite element model

(a) Property setting of common concrete material
(b) Property setting of UHPC material

Figure 6. Material property parameter setting diagram.

(a) Definition of surface heat radiation
(b) Definition of surface heat transfer

Figure 7. Partial key parameter setting diagram.

In this study, a uniformly distributed thermal radiation field was used on the outer surface of the UHPC to simulate the chloride ion erosion environment in the saline-alkali land in this project. The project conducted survey and research on the soil properties of the location, and the monitoring results of soil corrosion are shown in table 1. This study selected the highest surveyed chloride ion content of 317 mg/kg and used this environmental parameter as a loading parameter in the model.
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### Table 1. Survey results on soil corrosion.

| ID  | Depth (m) | Water Content (%) | PH  | Anion (mg/kg) | Cation (mg/kg) | Soluble Salt (mg/kg) |
|-----|-----------|--------------------|-----|---------------|---------------|----------------------|
|     |           |                    |     | CO$_2^-$      | HCO$_3^-$     | SO$_2^-$            | Cl$^-$ | Ca$^{2+}$ | Mg$^{2+}$ | K$^+$ |       |
| 1   | 0.3-0.5   | 14.2               | 8.71| 25            | 635           | 62                  | 20     | 158       | 59       | 147   | 1106  |
| 2   | 0.2-0.4   | 15.6               | 8.82| 20            | 650           | 59                  | 19     | 169       | 45       | 118   | 1080  |
| 3   | 0.3-0.5   | 14.1               | 8.76| 35            | 667           | 65                  | 25     | 170       | 55       | 142   | 1159  |
| 4   | 0.1-0.3   | 16.3               | 8.85| 15            | 640           | 66                  | 19     | 165       | 66       | 118   | 1089  |
| 5   | 0.6-0.8   | 12.2               | 9.03| 35            | 537           | 68                  | 20     | 114       | 51       | 131   | 956   |
| 6   | 0.1-0.3   | 11.4               | 8.56| 20            | 662           | 71                  | 26     | 172       | 58       | 142   | 1151  |
| 7   | 0.5-0.7   | 13.7               | 8.45| 51            | 273           | 715                 | 304    | 81        | 104      | 137   | 1665  |
| 8   | 0.3-0.5   | 12.6               | 8.91| 62            | 270           | 538                 | 251    | 79        | 93       | 121   | 1414  |
| 9   | 0.2-0.4   | 4.7                | 8.57| 41            | 208           | 469                 | 203    | 95        | 88       | 107   | 1211  |
| 10  | 0.3-0.5   | 2.4                | 8.35| 46            | 256           | 636                 | 291    | 66        | 82       | 146   | 1523  |
| 11  | 0.8-1.0   | 2.6                | 8.50| 20            | 256           | 210                 | 38     | 106       | 32       | 55    | 717   |
| 12  | 1.3-1.5   | 2.4                | 8.54| 21            | 263           | 267                 | 46     | 98        | 34       | 96    | 825   |
| 13  | 0.3-0.5   | 4.6                | 8.91| 42            | 257           | 432                 | 166    | 119       | 83       | 147   | 1246  |
| 14  | 0.3-0.5   | 21.7               | 8.60| 72            | 283           | 738                 | 317    | 86        | 99       | 186   | 1781  |
| 15  | 0.3-0.5   | 19.1               | 8.94| 81            | 305           | 719                 | 284    | 69        | 98       | 179   | 1735  |
| 16  | 0.3-0.5   | 17.3               | 8.58| 67            | 221           | 588                 | 259    | 67        | 65       | 166   | 1433  |
| 17  | 0.5-0.7   | 16.5               | 8.76| 62            | 248           | 643                 | 284    | 76        | 98       | 182   | 1593  |
| 18  | 0.3-0.5   | 14.2               | 9.07| 55            | 216           | 472                 | 205    | 113       | 67       | 129   | 1257  |
| 19  | 0.3-0.5   | 23.6               | 8.93| 69            | 281           | 764                 | 291    | 85        | 114      | 184   | 1788  |
| 20  | 0.2-0.4   | 2.8                | 8.41| 52            | 240           | 596                 | 249    | 65        | 84       | 176   | 1462  |

Select Hearttransfer in the analysis step, set the increment size and time interval of each step reasonably, do not check the geometric nonlinear calculation option. Since temperature field is the target, no stress will be generated during the temperature rising process, no need to set up boundary and load conditions; these values are to be set in statics analysis. At the end, the calculation is started, and the calculation and analysis are performed according to the constant external concentration, and the calculation time increases gradually.

In the meanwhile, this study also used common concrete to establish a comparative model, the model diameter is 1000mm, and the unit division also used concrete with eight-node DC3D8 3-dimensional real heat transfer unit. The rest of the environmental parameter settings are the same as the UHPC-NC composite cross-section model. The calculation resulted in two finite element models as shown in figure 8 and figure 9 below.

![Figure 8](image-url) **Figure 8.** UHPC-NC composite normal cross-section calculation field cloud diagram.

![Figure 9](image-url) **Figure 9.** Normal cross-section of normal concrete calculation field diagram.

Combining with computational cloud chart shown in the figure, the outer envelope of UHPC can effectively block the transmission of chloride ions from the external environment to the center of the
cross section. It can be seen from the cloud distribution in the figure, under the same external condition and operation time, the penetration depth of chloride ion in the UHPC-NC composite section is much smaller than that in pure normal concrete section. It can be seen that the UHPC-NC composite cross-section can prevent the penetration of chloride ions in a saline-alkali environment, thereby effectively improve the durability of the transmission structure foundation, and hence ensuring the safety and applicability of the electric transmission structure during the operation phase.

6. Conclusion

- The durability study of UHPC-NC composite pile foundation of electric transmission tower in saline-alkali region, using computer research technology to formulate the corresponding artificial acceleration test of the natural environment can more directly and effectively reflect the durability issue of the actual project.
- The finite element calculation cloud diagram shows that under the same environmental conditions and action time, the penetration depth of chloride ion in the UHPC-NC composite cross-section is much smaller than that in pure common concrete cross-section.
- The outer wrap ring of UHPC can effectively block the transmission of chloride ions from the external environment to the center of the cross-section; UHPC-NC composite cross-section can prevent the penetration of chloride ions in saline-alkali environment; thereby, it can effectively improve the durability of the electric transmission structure foundation and increase the durability of the transmission structure foundation and further ensure the safety and durability of the electric transmission structure in operation phase.

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