The true working performance inversion simulation analysis of Jinping level-I arch dam

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Abstract. Jinping Level-I Super-high Arch Dam, which is up to 305 m high, ranks the highest among all the arch dams that are built up and under construction in the world. But various technical problems have appeared in the design and construction of the super-high arch dam. Therefore, it is necessary to precisely evaluate and predict the temperature, stress and deformation and address the working performance well during the construction, which is critical for the dam construction quality and safe operation of the dam. By performing a whole-dam whole-process simulation analysis, the paper discusses the true load simulation, the simulation of the transverse joint, adiabatic temperature rising model and efficient technologies to resolve difficulties for the super-high arch dam. The whole-dam whole-process simulation analysis platform – SapTis is used to conduct simulation computation in order to track the true working performance of Jinping Level-I super-high arch dam during its construction. Through analysis of the monitoring data and inversion simulation of the computation parameters, the paper simulates the current working performance of the dam, predicts late-stage response, researches the various problems occurring in the construction to come up with effective solutions. The use of the inversion simulation analysis helps have a whole picture of the true working conditions and performance of the dam during its construction, water impounding and operation and guarantee the dam construction quality and operation safety, while creating a new technology solution for the control of high arc dam construction quality.

1. Introduction
The maximum dam height of a Double Curvature Arch Dam of Jinping Level-I hydropower station is 305 m, which ranks the highest arch dam under construction in the world. With the completion of Jinping Level-I Extra-high Arch Dam, the construction of high arch dam in our country is being realized the leap from the following to the leading. There is a significant performance difference between the Level-300 m extra-high arch dam and the Level-200 m arch dam [1], first, the stress level of Level-300 m extra-high arch dam is high, its main tensile stress control is different from that of ordinary arch dam, both tensile and compressive stress of extra-high arch dam reach the critical value of standard allowable stress, the overall safety margin may be less than ordinary arch dam; second, working performance and stress in construction period will have a great influence on the operation later state, so that the true working performance of the dam is different from the initial design state greatly, third, because extra-high arch dam bottom width is bigger, later concrete temperature rise greatly, difficulty of temperature control and crack prevention increase [2], its requirement on spatial gradient when water cooling is high, result in the increase of cantilever height, it may lead to the deterioration of working condition of arch dam during construction period. In some cases, working
performance may occur safety control condition during the construction period.

The article takes Jinping Level-I Extra-high Arch Dam as the study object, considering the complex topographic and geological conditions in dam area and various boundary conditions of arch dam construction period, from the beginning of dam pouring and carry out simulation analysis and back analysis and according to actual construction progress, environmental boundary, monitoring data, construction quality and other factors of the arch dam to veritably, reliably understand the working performance of arch dam and further guide the construction and ensure the safety operation of the dam.

2. Whole dam whole process simulation analysis method and software

The whole dam whole process simulation analysis method is an important method to study the true working performance of Jinping Level-I Extra-high Arch Dam [3], and there are three basic characteristics of this method, first is the whole dam, carry out simulation for the whole dam including all transverse joint, fillet, orifice, pier, complex geological conditions; second is the whole process, need to simulate the working performance of the dam construction period, the initial filling and the operation period from the pouring of first hopper of concrete of the dam, third is simulation, get close to the true state as far as possible from the aspect of model, boundary condition, construction process, calculation parameters and others. For Jinping Level-I Arch Dam, mainly from the following aspects to ensure the implementation of working performance inversion simulation during construction period.

2.1. Fine finite element grids

Carry out finite element modeling according to actual excavation on site, foundation treatment, structure design and the latest geological data, the model reflects the accurate figure, detail structure, and various joints of pedestal and dam, to fit the temperature field analysis requirements during pouring, when dividing grids, pay attention to fine degree of grids and gradient change grids in the position of upstream and downstream surface of dam, foundation cushion, baseboard and others contacting with water and air; the basic model reflects the complex geological structure, Including partitions of various rocks (Type II, Type III1, Type III2, Type IV1, Type IV2 and Type V1), complex fault (f2, f18, f5, f8, f42-9, f13, f14 and X), A variety of treatment measures for the ground (anti-shear hole, grouting, backfill, etc.), various treatment measures for foundation (anti-shear tunnel, grouting, backfill, etc.). The models are shown in the figure 1.

![Figure 1. Finite element computational grid model of Jinping level-I arch dam. (a) Foundation, (b) Dam body and (c) Various joints.](image)

2.2. True load simulation

At present, the loads playing the important role in dam deformation including self-weight, water pressure and temperature. The load simulation adopts whole process simulation analysis method, simulate the construction process of the dam, Stage by stage simulate the function of self-weight and water pressure, simulation of temperature load starts from the day of concrete pouring, accurately considering the various environmental temperature and temperature change of concrete itself, considering the whole process of temperature load, at the same time, according to the monitoring data
during the construction process to carry out feedback on internal temperature process of dam, to make the load simulation get closer to the actual situation.

2.3. Simulation model of transverse joints true performance

Transverse joints performance has important influence on arch dam performance. In the early stage of pouring, due to temperature rising transverse joints in compacting state, transverse joints can pass compacting and shearing action, is of less tensile strength; during the cooling process, the temperature drops and it shrinks, the transverse joints opens, and the transverse joints have a certain degree of opening; after closure grouting of dam, the transverse joints interim is filled, transverse joints can pass compacting and shearing action, with a certain tensile strength. The Simulation of true performance of transverse joints, innovatively through the study of the contact surface opening and closing iteration algorithm, to establish concrete contact surface model which can simulate the actual opening and closing process of transverse joints. When disposing the opening and closing iteration of contract surface elements, to prevent the above problems caused by the contact surface embedding, the state variable of the contact surface model is introduced, record the opening and closing state of contact surface before and after each iterative step, when the unit state is considered no longer changed the iteration converge; at the same time, in each iteration step adopt the method of pre-judging the status of the contact surface, promptly increasing decreasing stiffness springs, addition and subtraction force, greatly speed up the convergence rate, under the premise of ensuring the reasonable calculation results, reduce the computational cost, which is suitable for large scale numerical calculation.

Additionally, through the derivation of stress-strain relationship of contact surface element with zero thickness key bed, establish the contact surface model which can simulate the trapezoid, triangle and spherical key bed. When establishing finite element model, the key bed in vertical and horizontal joints shall be simulated carefully, the workload is huge, and it is difficult to operate at the same time, Therefore, it is very effective to simulate mechanical behavior of key bed with contact surface equivalent key bed model. As for the spherical key bed shown in figure 2, the contact stiffness can be described by the following formula:

\[
[D] = \begin{bmatrix}
\alpha_n K_s & 0 & 0 \\
0 & \alpha_h K_s & 0 \\
0 & 0 & \alpha_n K_n
\end{bmatrix}
\]  \hspace{1cm} (1)

![Figure 2. Spherical key bed model diagram. (a) Open and (b) Open sideslip.](image)

In formula (1), Kn, Ks is normal, tangential contact stiffness, \( \alpha_h, \alpha_n \) are related to the following three states:

- \( \delta_n \leq 0 \), close, \( \alpha_n = 1 \), \( \alpha_h = 1 \)

- \( \delta_n > 0 \), \( \left| \delta_h \right| \geq R \sin \beta - \sqrt{R^2 \sin^2 \beta - 2R \delta_n \cos \beta - \delta_n^2} \), open: \( \alpha_n = 0 \), \( \alpha_h = 0 \)

- \( \delta_n > 0 \), \( \left| \delta_n \right| \geq R \sin \beta - \sqrt{R^2 \sin^2 \beta - 2R \delta_n \cos \beta - \delta_n^2} \), open the sideslip, shear of lateral
contact: $\alpha_n = \xi \cos \beta, \beta_n = 2.5 \xi \sin \beta$

2.4. Post heating adiabatic temperature rising model
In recent years, high arch dam after being water cooling and temperature decrease, there is a big rebound in temperature; the temperature of some is still rising even in the age of six months to a year. We propose a combined function model on the basis of conventional formula [4] for it, as shown in the formula (2), which can more flexibly accurately simulate the actual hydration heat process of concrete, so as to calculate the temperature field and the temperature stress of the whole process.

\[
Q(\tau) = Q_2 \left( 1 - e^{-\alpha_2 \tau^3} \right) + Q_2 \left( 1 - e^{-\alpha_2 \tau^3} \right)
\]

\[
Q(\tau) = Q_1 \frac{\tau^{\beta_1}}{\alpha_1 + \tau^{\beta_1}} + Q_2 \frac{\tau^{\beta_2}}{\alpha_2 + \tau^{\beta_2}}
\]

\[
Q(\tau) = Q_2 \left( 1 - e^{-\alpha_2 \tau^3} \right) + Q_2 \left( 1 - e^{-\alpha_2 \tau^3} \right)
\]

(2)

2.5. Efficient parallel algorithm of equation set solution
Considering the huge simulation calculation of whole dam whole process, an efficient parallel algorithm is developed; considering the flexibility and extensibility of the software, equation paralleling solvers are developed respectively based on OMP and MPI platform. Adopt parallel algorithm for sparse direct solution based on incomplete LU factorization and efficient Krylov subspace iteration method combined with pre condition technique and other methods to realize efficient solution of linear algebraic equations of super-large scale massive computation.

2.6. Whole dam whole process simulation analysis platform - SAPTIS
SapTis [5,6] is a large-scale structure multi-field simulation and nonlinear analysis software with more than 20 years of development and application history, has been equipped with a variety of functions such as pouring of concrete dam, excavation of cavern, temperature, seepage, deformation, stress and other multi-field simulation, structural nonlinear analysis and others, which can be used in simulation analysis of temperature stress, seepage, stress, deformation and safety degree and others of simulating the concrete dam from foundation excavation, pouring, filling, until the whole process of long run. The software entire process consider the construction process, temperature boundary conditions, concrete hydration heat, water cooling process, elastic modulus variation process, creep degree and others in complex concrete structure. By real-time simulation, grasp the spatial and temporal distribution of temperature, deformation and stress of concrete structure and true working performance of engineering structure. So far, it has been applied in Three Gorges, Ertan, Longtan, Xiaowan, Xiluodu, Jinping, Danjiangkou, and other dozens of engineering, and achieved good results. SapTis software platform is the core computing platform of true working performance inversion simulation analysis of Jinping Level-I Arch Dam.

3. Inversion of foundation and dam deformation modulus
The thermal and mechanical parameters of materials are the basis of the simulation analysis; it is short of monitoring data in early construction phase, generally according to the design parameters and the test parameters of site and test room, to reflect the dam and basic real thermal and mechanical properties as far as possible. With the accumulation of monitoring data, shall according to the site actual temperature, deformation and other monitoring data, through the whole process simulation calculation, carry out inversion and feedback analysis of physical and mechanical parameters of dam and foundation, calibration analysis model input parameter, to ensure that temperature field and stress field calculation result can truly reflect the actual situation of the engineering.

For Jinping Level-I Arch Dam, first, the feedback of the temperature field is carried out, make the calculated temperature process coincide with actual measured temperature process by adjusting the parameters and conditions of temperature calculation, then take advantage of temperature field
obtained by feedback, and based on the dam deformation monitoring data, to carry out further feedback analysis for material parameters of dam and bedrock. In the feedback analysis, considering the little change of density, poisson ratio and linear expansion coefficient and other parameters and other thermal parameters, therefore, its value is selected according to the design value or the test value, and assumed that the value is fixed, only change variable modulus values of dam body and foundation model. The basic idea of feedback analysis [7,8] is to make the calculated dam displacement of finite element model get close to actual measured dam displacement as far as possible by continuously adjusting variable modulus values of each partition of dam concrete and different types of rock of foundation in finite element model. When the calculated results and the actual measured deformation mean square error take the minimum values, the taken model modulus value is considered to be more realistic elastic and deformation modulus value of dam concrete and bedrock.

The geological condition of Jinping Level-I Arch Dam is complex, the foundation surface layer is mainly Type ⅡⅡ2 and Type ⅣⅠ1 rock mass, the interior is mainly Type ⅢⅠ1 and Type Ⅱ rock mass, the deep part is mainly Type ⅢⅠ rock mass. According to the vertical monitoring results and gallery settlement monitoring results, from the geological survey data, the actual measured data of surface rock mass is more adequate, due to the technical condition of deep rock mass, its geological prospecting data is not enough, therefore, when foundation deformation modulus inversion, adopt actual test values for surface layer with Type ⅡⅡ2 and Type ⅣⅠ1 rock mass, carry out inversion for variable modulus of interior Type ⅢⅠ1 and Type Ⅱ rock mass, for the deep rock mass (below 1400 m), its rock mass deformation modulus is determined by the empirical relationship between ground stress and deformation modulus, no more inversion here. In addition, according to the law of the dam gallery settlement observation value in the monitoring data, subdivide local area of dam foundation, carry out variable modulus inversion. Carry out inversion for the elastic modulus of dam body and the pedestal on the basis of the designing elastic modulus. Due to the large number of parameters of the dam and the foundation material, it is necessary to carry out repeated trial calculation to approach the correction target of the dam and the foundation material, therefore, use orthogonal test method to determine inversion sample, then combine the monitoring data with effects of dam and foundation variable modulus, to finally determine each inversion calculation conditions. Inversion ideas based on vertical displacement and horizontal displacement are as follows:

- **Vertical displacement**

  The relationship between the vertical displacement and the dam body, the foundation variable modulus parameter is close, vertical displacement of measuring point in different position can respectively reflect deformation characteristics of dam body and foundation. Because the low-elevation gallery is close to the dam foundation, its vertical deformation data mainly reflect the influence of bedrock deformation, take the deformation of this section as feedback target, can carry out vertical variable feedback correction for the Grade ⅡⅡ2 rock mass, Type Ⅱ rock, weak structural plane and other materials in foundation bottom; galleries vertical displacement difference of other galleries of upper elevation and other adjacent elevation is less affected by the foundation variable modulus, it can basically reflect the influence of the dam concrete modulus of the elevation section, take each gallery displacement difference as feedback target, preliminary estimate dam body deformation modulus value; also according to the deformation difference of multi-point displacement meter, can estimate the foundation deformation modulus value; then combine vertical data, gallery level and other monitoring data, to carry out feedback correction for dam concrete and foundation modulus.

- **Radial displacement**

  The radial displacement of dam is also affected by dam body, foundation variable modulus parameters. Take radial displacement of dam as feedback target; on the basis of roughly estimate dam body variable modulus according to adjacent elevation gallery deformation difference can carry out feedback correction for dam concrete variable modulus.

  Monitoring data reflect that, with the increase of dam body pouring elevation, under the overhang
effect, the dam is gradually shifted to the upstream; with filling to 1710 m elevation, 1760 m elevation, 1800 m elevation and 1840 m elevation, the dam is gradually deformed toward downstream, middle and low elevation displacement is larger than middle and high elevation, at present, the maximum radial displacement is about 27 mm; gallery level monitoring data show that the whole dam is in a state of subsidence, the subsidence of middle section is larger, the subsidence of both sides is less, of basic symmetric distribution, local section on both sides is of slightly elevated vertical displacement change trend. Figures 3 and 4 are the radial displacement of the dam and the vertical displacement monitoring curve graph at the initial filling stage.

Figure 3. 13# dam section vertical radial displacement actual measured process line.

Figure 4. Vertical displacement of dam 1664 m elevation distribution map.

Figure 5. Typical warehouse temperature process feedback curve.

Figure 5 is the contrast curve of feedback temperature and actual measured temperature of typical warehouse, make the calculated temperature process coincide with actual measured temperature process by adjusting the parameters and conditions of temperature calculation, based on this,
according to the dam deformation performance reflected by monitoring data, carry out inversion for dam and foundation elastic modulus by the method of whole process simulation analysis. Figure 6 is settlement diachronic curve comparison of 1778 m elevation gallery in some period of 17# dam section and 1601 m elevation gallery of 13# dam section, figure 7 is vertical radial displacement and calculated value contrast curve of typical parts of typical dam section, it can be seen that the calculated and measured processes are consistent, and the deformation modulus obtained by inversion can reflect the true performance of the dam.

Figure 6. Relative settlement of gallery level of different dam sections diachronic contrast grap. (a) 1778 m gallery of 17# dam section (b) 1601 m gallery of 13# dam section.

Figure 7. Working performance analysis of transverse joints during construction. (a) 1730 m elevation and (b) 1601 m gallery.

4. Working Performance Analysis of Transverse Joints during Construction

4.1. Monitoring data analysis of transverse joint opening degree during construction
The monitoring data of Jinping Level-I Arch Dam during construction period shows that Most of the opening process of transverse joints is very well correlated with the temperature, early concrete temperature rise, transverse joints in compacting state, with water cooling the temperature of internal concrete of dam body drop, the transverse joints opening degree gradually increase and reach the maximum transverse joints opening degree before grouting, the maximum value of the transverse joint opening degree is generally less than 3 mm, which conform to the general rule, after grouting, the opening degree of the transverse joints basically remain unchanged. But the transverse joints opening degree of some dam sections is larger, and there is obvious abrupt change, mutation time is close to the grouting time, the maximum transverse joints opening degree of some parts is more than 8 mm, which does not conform to the general rule of the transverse joints opening degree. Figure 8 is the abnormal joints opening degree monitoring data diagram.
Figure 8. Actual measured transverse joints opening degree. (a) Transverse joints opening degree diagram and (b) typical transverse joints opening degree process line.

Figure 9. Transverse joint opening degree process line after grouting.

In addition, the joint meter shows that there are different degrees of opening in the transverse joints in already grouting area of the lower part of the arch dam during construction period. As shown in the figure 9. after arch dam closure till June 20, 2012, the opening degree of 10# transverse joint in EL1620 m-EL1680 m is larger, the opening degree reached 0.4 mm-0.9 mm; opening degrees in the rest elevation are smaller, the opening degree is about 0.1 mm. 13# transverse joints opening degrees above EL1620 m are less than 0.2 mm; its opening degrees below EL1620 m are larger, opening degree in the upstream of EL1585.7 m reaches 2.42 mm, and there is abrupt change of opening degree.
Most of the elevation opening degrees of 16# transverse joints are less than 0.15 mm, individual larger elevation opening degree reaches 0.31 mm. Therefore, analyze the causes of abnormal phenomenon of transverse joint opening degree, and to analyze its harmfulness, and further take the corresponding control measures.

### 4.2. Problem analysis on oversize partial transverse joint opening degree in construction period

For the problem of oversize partial transverse joint opening degree in the construction period, through the method of whole process inversion simulation analysis, on the basis of the inversion of actual temperature field and main mechanical parameters, carry out simulation in accordance with the actual construction process, temperature control process and closure grouting process of dam, the calculation parameters consider the concrete elastic modulus change with time, concrete creep, concrete autogenous volume deformation and other factors, respectively analyze the influence on transverse joint opening degree under the synthetic effect of self weight, temperature, autogenous volume deformation and other factors and various factors. In addition, through the analysis of monitoring data, it is found that the time of occurrence of the opening degree is consistent with the transverse joint grouting time, and the transverse joint positions with abrupt change are all above grouting area, the higher the elevation, the greater the influence, it is speculated that the transverse joint opening mutation abrupt change is related to transverse joints grouting according to time anastomosis; therefore, carry out corresponding simulation for grouting pressure degree, grouting method, analyze the influence of grouting factor on transverse joint opening degree.

The simulation results show that [9], the effect of the self weight on the average joint opening degree is about 0.2 mm; under the effect of autogenous volume deformation, under the condition of design parameters, the transverse joint opening degree is 0.18-0.53 mm, the average value is 0.39 mm; under the condition of temperature and autogenous volume deformation, the average value of transverse joint opening degree is 1.93 mm, the maximum is 2.9 mm. Under the synthetic effect of self weight, temperature, concrete autogenous volume deformation and other factors, the change law of calculated transverse joint opening degree is the same as monitoring value, early concrete temperature rise and expansion, transverse joint is in compacting state, with the decrease of the temperature of the dam, the transverse joints gradually open, and the maximum value is reached when the temperature reaches the minimum. In the abrupt change position of transverse joint opening degree, the difference between the calculated value and the monitoring value is large; the calculated value is close to the monitoring value after the removal of abrupt change. Therefore, in order to analyze the influence of grouting, carry out sensitivity analysis respectively for whether through horizontal pressure or not, grouting pressure degree, pressure impose height and others, simulation calculation results shows that: The grouting pressure has little effect on the transverse joint opening degree when through horizontal pressure, and the influence scope is limited to the grouting elevation nearby, and the effect of the joint opening degree in grouting area is less than 0.3 mm; when do not through horizontal pressure, the grouting pressure affects the transverse joint opening degree of upper part, and it is of increasing trend with the increase of height, the upper part reach 1.39 mm in 9 m under the pressure of 0.5 MPa, the greater the pressure area, the greater the transverse joint opening degree, the maximum value is 5.98 mm in 18 m grouting area under the pressure of 0.5 MPa. The results are shown in the figure 10 and figure 11. Combine monitoring data and simulation results, it can be seen that grouting method is the main reason affecting transverse joint opening degree, shall strictly in accordance with the relevant requirements of the grouting operation in the actual construction process.
4.3. Partial opening problem of transverse joint after grouting during construction period

For opening problem of the transverse joint after grouting, also through the method of whole process inversion simulation analysis, on the basis of the analysis of the monitoring data and on the basis of the inversion of the actual temperature field and the main mechanical parameters, carry out simulation analysis according to actual pouring process and the closure process of the dam, focusing on the cause of transverse joint opening after closure, carry out quantitative analysis from self weight, temperature and other aspect affecting factors, the analysis results show that [10]:

- Take 10#, 13# and 16# transverse joints as the research objects, considering the combined effects of weight and temperature, by June 20, 2012, the average value of calculated the transverse joint added opening degree after closure was 0.26 mm, the monitoring value was 0.19 mm, the calculated values and monitoring values were slightly different, but the law of the two is basically the same, the 13# transverse joints added opening degree in dam section of river bed upstream is that the upstream is bigger than that of downstream, 10#, 16# transverse joints added opening degree in dam section of slope is that the downstream is bigger than upstream. Considering the effect of self weight alone, the average value of transverse joints added degree is 0.2 mm, considering temperature effect alone, he average value of transverse joints added degree is 0.06 mm, self-weight plays a major role in transverse joint opening after closure. The results are shown in the figure 12.
- For the position of transverse joint added opening degree with abrupt change after grouting,

![Figure 10. Contrast of process line of simulation calculation and actual measurement and joint opening degree after deduction of abrupt change value.](image1)

![Figure 11. Influence of grouting on joint opening degree curve.](image2)
through the analysis of the monitoring data, there is pressurized water operation before joint grouting at the moment of abrupt change in upper grouting area, affected by it; there are abrupt changes in the transverse joint open degree of already grouting lower part.

![Figure 12](image)

**Figure 12.** 13# dam section transverse joint opening degree process line.

4.4. Impact analysis on oversize transverse joint opening degree and added opening problem

The oversize transverse joint opening degree during construction process, and there is the trend of development after grouting, therefore, it is necessary to study the influence of oversize transverse joint opening degree on the dam's stress.

Before closure grouting, the parts above closure elevation are separate bearing load of each dam section, when designing in accordance with the consideration of the working condition, and calculate the height of the cantilever, the oversize transverse joint opening degree will not affect the stress at this moment. While closure grouting, big transverse joint opening degree is beneficial for the entry of grouting slurry. As long as the design is elaborate, the construction is meticulous, ensure grouting quality, guarantee the grouting compaction, after the hardening of grouting slurry, it is basically equivalent to concrete body elastic modulus. After grouting, the dam will become a complete whole, which does not affect the dam stress. After closure grouting, the already grouting transverse joint opening degree continue to develop under the effect of upper self weight, and grouting and various factors, if cause opening of the already grouting transverse joint, it will have a negative impact. The article through the method of whole process simulation analysis to simulate the actual the actual opening degree of the transverse joint and the open state after grouting, from the construction period simulation calculation to the dam filling, calculation results show that: after filling, under the effect of water pressure, transverse joint need to be close first so that it can arch bear hydro-thrust, displacement along river and tensile stress of dam heel will increase. According to the transverse joint opening situation reflected by monitoring data, after the filling to 1880 m, displacement along river growth rate is 3.07%; the dam body stress distribution law remain unchanged, the extreme value of tensile stress of dam heel will increased by about 5%, tensile stress range will increased by 0.2 m.

Therefore in the process of construction, shall strictly in accordance with the technical requirements of grouting to carry out operation, especially to achieve “when carry out grouting for transverse joint in an elevation, shall through horizontal pressure for no grouting adjacent transverse joint of the same elevation [11]”. At the same time in order to reduce the influence of self weight on the transverse joint opening, shall take timely measures such as upstream water filling and others.

5. Construction period overhang and control of whole arch dam

Overhang is one of the main features of hyperbolic double curvature arch dam, in the process of construction, overhang has some effects on the stress and deformation of dam, poor control will bring the stress state contrary to the normal load of the design, even produce adverse effects on the dam structure. Jinping Level-I Arch Dam is higher than 300 m, the problem of overhang is more prominent during construction, especially the overhang of upstream surface, if the control is poor, it is easy to
occur larger tensile stress on downstream surface, or even occur cracks; in addition, upstream deformation brought by overhang effect may bring about the opening of transverse joint in local area, so it is necessary to study overhang problem of Jinping Level-I Arch Dam during construction, and put forward corresponding measures.

In order to study the working performance of dam in overhang state, according to existing specification requirements, adopt whole process simulation analysis method, establish the model of whole dam, considering the influence of self weight, water pressure and temperature load, carry out calculation for various overhang working conditions which may occur during construction period by using finite element equivalent stress method, carry out evaluation in accordance with the corresponding stress control standards. The stress state at different stages of the dam under the condition of empty reservoir and various water filling conditions is mainly studied.

Simulation calculation results show that: under the effect of self-weight in empty reservoir the Jinping Level-I Arch Dam will produce a certain range of tensile stress near the foundation surface of downstream surface, because the dam overhang has the trend of tilting to riverbed and the trend of tilting to upstream, the first principal stress of downstream is greater than that of the upstream. As shown in the figure 13, the direction of principal stress makes an acute angle with foundation surface, which explains that the first principal stress is produced by the combined effects of high shear stress of foundation surface along the steep slope and downstream tensile stress caused by overall overhang. The large tensile stress in the position may lead to the foundation surface disengaging, or occurring cracks in the nearby area, which needed to be concerned about. Take the image empty reservoir state in May 2012 for example, after making equivalent upstream surface tensile stress is 1.1 MPa, which do not exceed the standard, but the downstream surface tensile stress reaches 2.1 MPa, the area exceeding the standard area is about 20 m², the depth is about 12 m. Considering the upstream water filling scheme, taking the upstream filling to the 1660 m elevation as example, the maximum downstream surface tensile stress is reduced to 1.8 MPa, the results are shown in the figure 14. In addition, the effect of the upstream water filling impoundment seam is very small, which can be ignored. Therefore, proper filling is favorable to reducing tensile stress near the downstream surface of foundation surface.

Figure 13. Cloud image and its vector diagram of downstream surface tensile stress under effect of overhang.
Therefore, in order to reduce the adverse effects of the dam overall overhang, high dam empty reservoir state shall be avoided. It can be adopted that select appropriate time to do upstream water filling, considering the river water temperature is lower than the temperature, water filling time shall be avoided in the low temperature season. During the construction of Jinping Level-I Arch Dam, Summer upstream appropriate water filling scheme is adopted, which guarantee the construction quality of dam and the safety during construction period.

6. Study on working performance of dam in initial filling stage
Jinping Level-I hydropower station started filling from guiding tunnel gate in November 2012, it is planned to filled to the normal water level of 1880 m by September 2014, according to the construction schedule of engineering, the dam pouring was still continuing in the initial filling, joint grouting was not completed, especially in October 2013 after guiding bottom gate, when the reservoir filling from 1800 m water level to 1840 m water level, the joint grouting elevation of the dam was about 1859 m, there was still 26 m of dam without joint grouting, in order to make the arch ring grouting of upper dam arch avoid the adverse effects of high water level pressure impoundment seam on the transverse joint grouting as far as possible, need to study the best opportunity of transverse joints closure grouting according to the reservoir water level and the project schedule.

In the initial filling stage dam is under construction, various design parameters may vary with the loading history and loading path, the compatibility between the strength of the dam itself and the actual boundary around the dam is not exactly consistent with the design expectation; and according to the dam accident statistics, it showed that, almost 60% of the dam accidents occurred in the initial filling stage or initial operation stage. Therefore, according to the monitoring data of each stage during the initial filling, carry out tracking and inversion simulation analysis for working performance of the dam, promptly grasp the current operation safety state of the dam, and make predictions for next safety status, to provide the decision basis for making safe operation monitoring standard and reservoir scheduling operation mode.

6.1. Analysis on impoundment seam problem of the initial filling
In the initial filling stage, the upper elevation closure grouting is not yet completed; the water pressure will produce impoundment seam effect on the no grouting transverse joint of upper different elevations. Simulate filling process, refer to the actual monitoring value of transverse joint, predict the effect of filling and arch closure scheme on the grouting of dam.

The simulation calculation results show that [12], in the same position, the overall transverse joint opening degree is in gradually compacted state with the rise of the water level, the higher the water level, the more severe the impoundment seam. The open degree of the downstream side of the arch
crown cantilever shows an open trend under the condition of lower water level. The change law of transverse joint opening degree near the riverbed is: severe impoundment seam is most severe on the upstream side at the same elevation, impoundment seam value decreased gradually from upstream side to the downstream side. The change law of transverse joint opening degree near the two sides is: severe impoundment seam is most severe on the downstream side at the same elevation, impoundment seam value increased gradually from upstream side to the downstream side.

According to the existing construction progress and filling progress, when the water level is below the 1800 m elevation, the total impoundment seam value is not large, and the average impoundment seam value is less than 1 mm; when the water level is elevated from 1800 m to 1840 m elevation, the average impoundment seam value is up to 1.35 mm, calculate according to current average joint opening degree of 1.83 mm based on monitoring data statistics, the remaining average joint opening degree is 0.48 mm. When the water level reaches 1840 m elevation, impoundment seam is larger is small scale of transverse joint, which is more than 2 mm, it is mainly concentrated in the parts above 1859 m elevation, so when the initial filling reaches to 1840 m elevation, it may have an effect on the closure grouting of these parts.

If considering reducing the water level to 1800 m by the end of February 2012, and then carrying out closure grouting in March-May, the total impoundment seam value would have a significant improvement compared with filling to 1840 m elevation, it is close to impoundment seam situation of first filling to 1800 m, the maximum impoundment seam value is generally less than 1 mm. So it can be considered that after the water level is reduced, select machine to closure grouting according to the actual monitoring joint opening degree situation. The current engineering is also drawing lessons from on the results of this research program.

6.2. Analysis on current working performance of dam
The finite element calculation results show that, in the process of filling, with the water level increased, the dam displacement along the river show an increasing trend toward downstream; at the same time, with the increase of delivery lift, the displacement increment becomes larger, increment of low elevation of dam is smaller, the higher the elevation is the upper point of the dam, with the increase of the water level, the more obvious the increment; left and right bank deformation is basic symmetrical , because considering the step by step pouring process of dam, at the same time, apply water pressure load according to normal filling time in the pouring process, so dam deformation contour is of stepped distribution. On tangential deformation, the left and the right bank of the dam are respectively pointing to the corresponding shore direction, and the left and right bank deformation is basic symmetrical. The whole deformation law of other points in time is the same as that of the water level, but with fluctuation of time and water level, the deformation value is different.

The vertical stress is basically compressive stress, and the maximum compressive stress value appeared in the bottom section of the dam, compressive stress gradually decreased from bottom to top, with the increase of the water level, the compressive stress of upstream surface is in decreasing trend, the compressive stress of downstream surface is in increasing trend. Except foundation surface local stress concentration point the upstream surface’s arch stress is all compressive stress, the stress is gradually increased from the periphery to the middle part, the maximum value of compressive stress occurs in the middle elevation of the arch crown cantilever, the maximum compressive stress is increased with the increase of the water level; when the water levels are 1810 m, 1820 m, 1830 m and 1840 m, the maximum stresses in dam heel (beam) are 8.5 MPa, 8.2 MP, 7.9 MPa and 7.2 MPa, the maximum compressive stress of the dam heel pressure actual measured is 6.66 MPa, appear in the 12# dam section, as shown in the figure 14. The simulation results are slightly different from the actual measurement [13], but the overall basically reflect the actual stress of dam heel.

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Figure 15. Cloud image of current stress calculation of dam (1839 m water level).

Figure 16. Diagram of vertical stress distribution of dam heel (November 20, 2013).

The general deformation and stress of the dam are shown in table 1 and figure 15, the overall displacement is consistent with the monitoring value, the dam body stress is in accordance with the general law, except the individual stress concentration point significantly exceeds the tensile stress, the tensile and compressive stresses were less than concrete tensile and compressive strength. In summary, the results of inversion tracking calculation analysis show that the current working performance of arch dam is generally normal.

| Elevation (m) | Monitoring Instrument | Water Level 1800 m-1839 m Radial Deformation Increment (mm) | Current Radial Deformation By November 20, 2012 |
|---------------|-----------------------|---------------------------------------------------------------|-----------------------------------------------|
|               |                       | Calculated value                                             | Monitoring value                              |
| 1778          | PL9-3                 | 12.03                                                        | 9.40                                          |
| 1730          | PL9-4                 | 7.23                                                         | 6.38                                          |
| 1664          | PL9-5                 | 1.41                                                         | 2.34                                          |
| 1778          | PL11-3                | 15.99                                                        | 13.94                                         |
| 1730          | PL11-4                | 11.88                                                        | 11.43                                         |
| 1664          | PL11-5                | 4.84                                                         | 6.13                                          |
| 1778          | PL13-3                | 16.65                                                        | 14.08                                         |
| 1730          | PL13-4                | 13.73                                                        | 12.16                                         |
| 1664          | PL13-5                | 7.64                                                         | 7.42                                          |
| 1778          | PL16-3                | 11.35                                                        | 9.95                                          |
| 1730          | PL16-4                | 9.72                                                         | 9.05                                          |
| 1664          | PL16-5                | 5.23                                                         | 6.13                                          |
| 1778          | PL19-3                | 4.36                                                         | 5.39                                          |
| 1730          | PL19-4                | 2.77                                                         | 4.50                                          |
| 1664          | PL19-5                | 0.93                                                         | 2.42                                          |
7. Conclusion
In the article, the key technologies of the whole dam whole process simulation analysis method are discussed, the whole dam whole process simulation analysis platform - SAPTIS is introduced from the true load simulation, the true performance simulation of the transverse joint, the post heating adiabatic temperature rising model, the efficient parallel algorithm of the equation set solution and other aspects. Use Saptis as the basic tool, and adopt the simulation analysis method to carry out inversion simulation analysis for the true working performance of Jinping Level-I Extra-high Arch Dam. (1) carry out inversion analysis for the foundation and mechanical parameters of dam concrete according to actual measured vertical and radial displacement, then carry out whole process simulation for the overall dam; (2) carry out simulation analysis for oversize partial transverse joint opening degree problem, the abrupt change problem of the transverse joint opening degree, the partial opening problem of the transverse joint after grouting during the construction period, study the causes, effects and improvement measures of these problems; (3) carry out detailed analysis and research for excessive tensile stress and possible crack problem caused by the overall overhang of arch dam during construction period, put forward suggested measures of advance filling to reduce overhang; (4) study the impoundment seam problem of the initial filling, put forward water level scheduling scheme which avoid affecting the quality of the upper closure grouting; (5) carry out whole process tracking inversion simulation analysis for the true working performance during filling process of dam, guide the simulation according to monitoring data, make accurate prediction for future performance, put forward proposed scheme which ensure the safety of dam.

The whole process tracking inversion and simulation analysis research and its application results show that, the simulation inversion method can grasp true working performance of the whole process of dam construction and filling, ensure the safety of the dam during construction and initial filling, the proposed technical measures and control measures have been adopted in the construction process, and achieved good results, guarantee the construction quality and construction, operation safety of the dam. At the same time, it created a new model of technical support for the high quality construction of the Level-300 m extra-high arch dam.

There are many contents in the working performance of the dam construction period and the initial filling period, limited to the length of the article, only describes the above aspects, a preliminary study has been done on temperature rise, the dam heel stress, tilting deformation, aging deformation, Initial seepage field effect and others, which will be introduced in the following articles.

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Conflict of Interests
The authors do not have any conflict of interest with the content of the manuscript.

References
[1] Zhang G X, Zhu B F and Jin F 2013 Summary report of study on the real working form of high arch dam and engineering application results (Beijing: Tsinghua University, China Institute of Water Resources and Hydropower Research)
[2] Zhang G X, Liu Y Z, Liu Y et al 2010 Discussion of the problem of extra-hig arch dam
temperature control and crack prevention *J. Hydrotech. Eng.* 29 125-31

[3] Zhang G X, Liu Y, Zhu B F and Wang R K 2008 Theory and method for the simulation of real working performance of high arch dam *Research Progress of Dam Technology and Long Term Performance 2008* 24-9

[4] Zhu B F 2009 *New Development of Theory and Technology of Concrete Dam* (Beijing: China Water Power Press)

[5] Zhang G X 2013 *SapTis: Development and application of multi-field simulation and nonlinear analysis software (one)* *Water Resour. Hydr. Eng.* 44 31-5

[6] China Institute of Water Resources and Hydropower Research 2013 Stress deformation of dam structure and safety evaluation during the construction period and initial filling of Jinping Level-I hydropower station (phase report Ⅱ)

[7] China Institute of Water Resources and Hydropower Research 2013 Stress deformation of dam structure and safety evaluation during the construction period and initial filling of Jinping Level-I hydropower station (phase report Ⅲ)

[8] China Institute of Water Resources and Hydropower Research 2012 Special research report of transverse joint opening degree analysis of 10# dam of Yalong Jinping Level-I hydropower station

[9] China Institute of Water Resources and Hydropower Research 2012 Analysis research report of causes and effects of opening of transverse joints after grouting in Yalong Jinping Level-I hydropower station

[10] Chengdu Survey Design and Research Institute of China Hydropower Consulting Group 2009 The joint grouting construction technology requirements of a Jinping Level-I hydropower station in Yalong River Sichuan Province

[11] China Institute of Water Resources and Hydropower Research 2013 Research of dam filling process control and selection of closure opportunity of Jinping Level-I hydropower station

[12] Zhang G X and Zhou Q J 2013 Causal analysis of the difference of the high arch dam heel stress actual measurement and elastic calculation results *J. Hydraul. Eng.* 44 640-7