The Application of Shell Elements in Concrete Face Rockfill Dams

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Abstract. The panel structure is one of the key technologies in the design of concrete face rockfill dams. In this paper, addressing the issue that a large number of isoparametric elements are required to reflect the stress characteristics of the panels to a certain extent, a method for automatically generating mid-surface shell elements was proposed based on the use of shell elements to replace isoparametric elements in simulating the panel structure of concrete face rockfill dams. When applied to the deformation analysis of the panel structure and its joints in concrete face rockfill dams, this method can accurately simulates the deformation of thin plates and the joints.

Keywords: Isoparametric elements; Shell elements; Finite element; Thin plate; Concrete face rockfill dam

1 Introduction

Concrete rockfill dam is widely used because of its advantages such as low cost and good adaptability to geological conditions[1]. In our country, concrete rockfill dams are surpassing the super-high dams in the 200 to 300 meter range[2-5]. As the scale and complexity of dam engineering continue to expand, there is an increasing demand for enhanced precision in numerical simulations[6]. In the context of concrete rockfill dams, the face plate serves as a critical component in ensuring the safety and integrity of the dam structure.

Shell elements typically use more complex form functions that are critical to the simulation of panel bending. However, it's difficult for the common isoparametric element to reflect the stress and bending characteristics of the panel. Therefore, Adina et al. established displacement plate element to replace isoparametric element[7-8]. Since then, scholars have mostly adopted the thick slab theory in Mindlin-Reissner[9-10] . But as the plate becomes thinner, shear latch occurs in the thick plate theory. In order to solve this phenomenon, scholars have proposed discrete Kirchhoff theory method[11], mixed interpolation method, etc.[12] to alleviate shear latching. Long Yuqiu et al. put forward the theory of generalized coordinating elements[13], which not only ensures the

Y. Zhang et al. (eds.), *Proceedings of the 2024 10th International Conference on Architectural, Civil and Hydraulic Engineering (ICACHE 2024)*, Advances in Engineering Research 259,
https://doi.org/10.2991/978-94-6463-658-1_64

convergence of the elements but also ensures that the generalized coordinating elements can be applied to the rectangular thin plate elements in a suitable hardness range, and then established a LGC-R12 quadrilateral displacement element[14] which can achieve higher precision. This element has been applied to square slab and semi-infinite foundation respectively in literature[15-17], but it has not been applied to the panel of concrete rockfill dam.

In this paper, shell element is used to replace isoparametric element, through this research, it's hoped to restore the force characteristics of the concrete rockfill dam panel with high precision and improve the efficiency of finite element analysis and calculation.

2 Simulation Methodology for Shell Elements

In order to ensure the displacement coordination between elements in the sense of average displacement, the generalized coordination shell element method is proposed. First, select the node displacement vector $\{q\}^e$ of the element, then set the deflection field ω in the element as polynomial, and set the undetermined coefficient of the polynomial as $\{\lambda\}$:

$$\begin{aligned} \omega = \lambda_1 + \lambda_2 \mathrm{x} + \lambda_3 \mathrm{y} + \ldots = [\mathrm{F}_\lambda]\{\lambda\} \\ \omega = \lambda_1 + \lambda_2 \mathrm{x} + \lambda_3 \mathrm{y} + \ldots = [\mathrm{F}_\lambda]\{\lambda\} \end{aligned} \tag{1}$$

The generalized coordination condition that the average displacements of adjacent elements at common edges are equal is applied to establish the relation of $\{q\}^e$ and $\{\lambda\}$, as follows:

$$[C]\{\lambda\} = \{d\} = [G]\{q\}^e \tag{2}$$

Where $\{d\}$ is the generalized displacement, it can be obtained:

$$\begin{cases} \{\lambda\} = ([C]^{-1}[G])\{q\}^e \\ \omega = [F_\lambda]([C]^{-1}[G])\{q\}^e \end{cases} \tag{3}$$

Finally, according to the differential relationship, the curvature is expressed by the deflection as:

$$\{n\} = [B]\{q\}^e \tag{4}$$

In summary, the stiffness matrix $[K]^e$ of the element is:

$$[K]^e = \iint_A [B]^T [D][B] dA \tag{5}$$

The above theory is applied to the bending problem of quadrilateral thin plate elements. The displacement vector $\{q\}^e$ of the unit node of the rectangular thin plate is taken as:

$$\{q\}^e = [\omega_1 \psi_{x1} \psi_{y1} : \omega_2 \psi_{x2} \psi_{y2} : \omega_3 \psi_{x3} \psi_{y3} : \omega_4 \psi_{x4} \psi_{y4}]^2 \tag{6}$$

Where, ω represents deflection and is set as a cubic distribution; $\psi_{\mathrm{x}} = \frac{\partial \omega}{\partial x}$ and $\psi_{\mathrm{y}} = \frac{\partial \omega}{\partial y}$ denote the turn angles and are set to be linearly distributed. The deflection field of the element ω is set as an incomplete quartic polynomial according to the ACM element:

$$\omega = [F_{\mathrm{x}}]\{\lambda\} \tag{7}$$

among,

$$\begin{cases} \{\lambda\}^T = [\lambda_1 : \lambda_1 \lambda_2 \lambda_3 : \lambda_4 \lambda_5 \lambda_6 : \lambda_7 \lambda_8 \lambda_9 \lambda_{10} : \lambda_{11} \lambda_{12}] \\ [F_\lambda] = [1 : \xi \quad \eta : \xi^2 \quad \xi\eta \quad \eta^2 : \xi^3 \quad \xi^3\eta \quad \xi\eta^2 \quad \eta^3 : \xi^3\eta \quad \xi\eta^3] \end{cases} \tag{8}$$

12 generalized displacements $\{d\}$ are selected to establish the generalized coordination condition. Since there are only 10 independent average displacements, the generalized displacement d11 and d12 adopt the corner of node 1. The twelve generalized coordination conditions are as follows:

$$[C]\{\lambda\} = [G]\{\mathrm{q}\}^e \tag{9}$$

3 Engineering Application

3.1 Project Introduction and Finite Element Model

This chapter takes the concrete panel rockfill dam of a Pumped Storage Power Station in China as the research object and applies shell elements in actual engineering to replace the isoparametric elements in the finite element calculation of the panel, thus verifying that the shell elements proposed in this paper can be applied and promoted in the finite element calculation of the panel rockfill dam.

The research object is a daily regulated pure pumped storage power station The normal reservoir water level is 716.0m, the dead water level is 691.0m, the design flood level is 717.32m, and the flood control level is 717.70m. The total reservoir capacity is

10.73 million cubic meters, the regulating reservoir capacity is 8.15 million cubic meters, and the dead reservoir capacity is 1.79 million cubic meters. The maximum dam height is 76.0m, the dam crest width is 10.0m, the panel thickness is 0.52m, and the panel thickness on the left and right dam heads is connected to the ring road, as shown in Figure 1.

The coordinate system used in the model calculation is taken as the origin of the coordinate system at the top left corner of the left shoulder dam axis on the dam crest; the X axis is taken as the cross-river direction, parallel to the dam axis, with the left bank to the right bank as the positive direction; the Y axis is taken as the river direction, perpendicular to the dam axis, with the downstream direction as the positive direction; and the Z axis is taken as the vertical direction, with the upward direction as the positive direction. The model element type is mainly hexahedral, with local transition to degenerate elements.

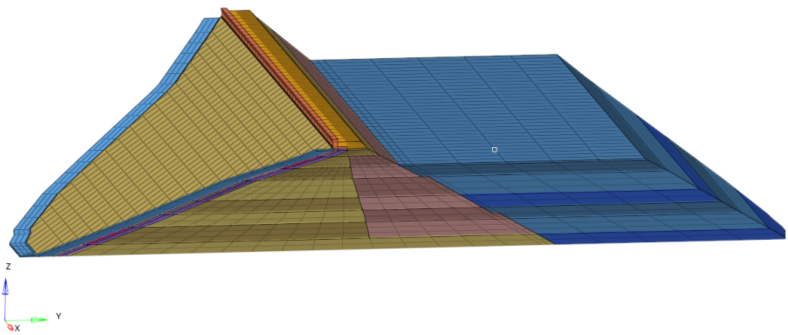
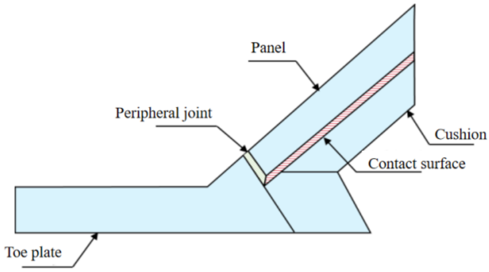
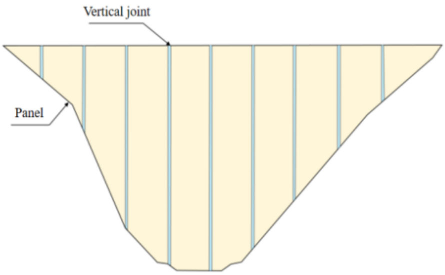


Fig. 1. Overall Calculation Model for Concrete Face Rockfill Dam

The panel part of this concrete face rockfill dam consists of 2,055 nodes and 1,224 elements. The element types are mainly hexahedral, with local transitions using degenerated elements. As depicted in Figure 2, the joint effects among panels, between the panel and the toe slab, and between the panel and the cushion layer all need to be considered. If the panel part is directly divided into shell elements, it is difficult to simulate and construct the relationship between the panel and its contact elements. Therefore, the generalized conforming shell element is employed to interpolate the isoparametric elements of the panel. The interpolation coefficients are obtained through the displacement relationship between the surface nodes of the panel isoparametric elements and the shell elements, thereby accurately simulating the vertical joints between panels, the peripheral joints between the panel and the toe slab, and the contact surfaces between the panel and the cushion layer.



(a) peripheral seam



(b) vertical seam

Fig. 2. Diagram of Panel Contact Joints

3.2 Material Parameters and Boundary Conditions

The materials of the dam are Duncan E-B, the contact surface between the panel and the cushion is simulated by Goodman element, and the peripheral and vertical joints. Table 1 to Table 2 list the mechanical parameters of the elastic material of the dam and the Duncan EB model material. The model is bound by the fixed boundary along the base boundary, the bottom, and the lateral boundary, the horizontal degree of freedom.

Table 1. Material Mechanical Parameters of the Linear Elastic Model for Dam

subregion	γ/ $KN\cdot m^{-3}$	E/ GPa	N
concrete	25.0	30.0	0.167

Table 2. Material Mechanical Parameters of the Duncan-Chang Model for Dam Structures

subregion	ρ/g· cm^{-3}	Φ/°	K	n	Rf	Kb	m
cushion	2180	55.3	1392.9	0.29	0.64	948.7	0.12
transition material	2160	55.6	1367.4	0.25	0.62	926.3	0.10
Main rock	2130	54.5	1258.1	0.23	0.62	763.1	0.09
Secondary rock	2050	51.5	776.1	0.28	0.64	458.7	0.14
Pressure slope body	2004	50.5	356.9	0.39	0.68	195.5	0.34
dam crest	2190	60.4	1323.6	0.28	0.61	1050.1	0.05

3.3 Comparison and Analysis

In order to apply shell elements to practical engineering problems, this chapter extends the unit to the face rockfill dam, verifies the effectiveness and evaluates the accuracy of the element applied to the face rockfill dam, and simulates the face deformation under different water levels during the completion and operation periods by using isoparametric element and shell element. The transverse deflection from the left bank to the right bank along the dam axis and the vertical deflection from the dam foundation to the dam top along the vertical line are analyzed respectively. The feature points taken in the horizontal direction are shown in the red wire frame in Figure 3, and the feature points taken in the vertical direction are shown in the blue wire frame in Figure 3.

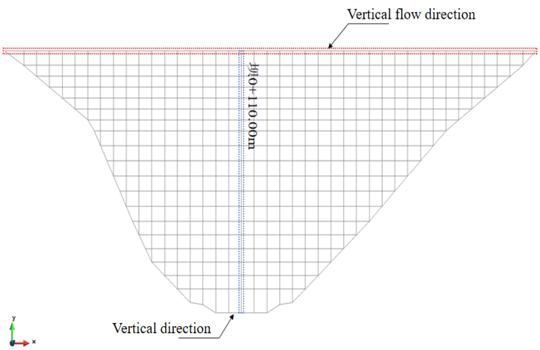


Fig. 3. Schematic Diagram of Panel Characteristic Points

In order to evaluate the performance and accuracy of the shell element simulation panel, the mesh of the reference element is encrypted along the thickness direction, from one layer to three layers. The deflection of the panel under the check water level is simulated by the isoparametric element of the first layer and the third layer grid respectively, and the simulation results are compared with those of the shell element. The transverse deflection change of the panel along the dam wheelbase is shown in Figure 4, and the vertical deflection change along the dam foundation distance is shown in Figure 5. It can be seen from the figure that the deflection of the panel simulated by shell element is consistent with the transverse and vertical deflection of the panel simulated by isoparametric element under the check flood level, showing that the deflection of the panel is the largest in the middle of the panel, and gradually decreases along the axis of the dam. The deflection along the dam foundation from the middle of the panel to the top and bottom of the panel gradually decreases, satisfying the objective law of engineering.

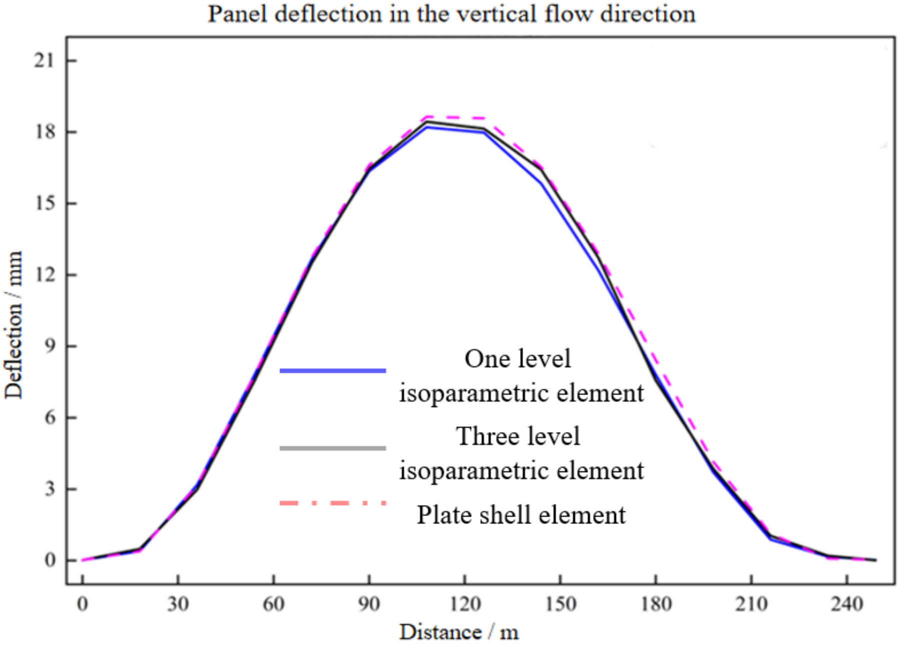


Fig. 4. Transverse Deflection Variation of the Panel along the Dam Axis

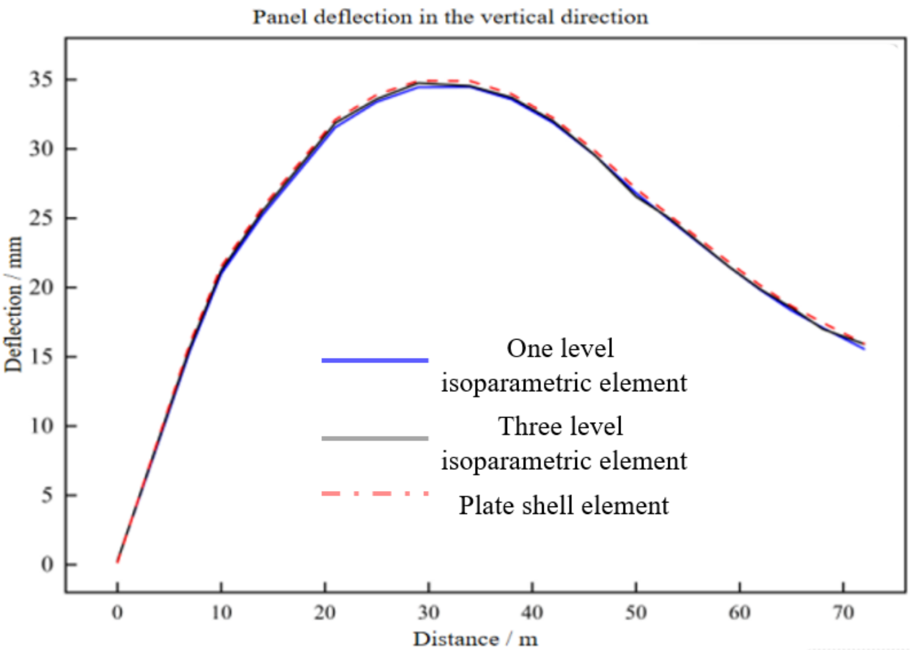


Fig. 5. Vertical Deflection Variation of the Panel along the Dam Foundation Distance

The finite element simulation results of one-layer isoparametric element, three-layer isoparametric element and shell element are compared, and the mean square error MSE of simulation results of shell and one-layer isoparametric element and three-layer isoparametric element are sorted into Table 3. Among them, the mean square error is used to measure the difference between the predicted value and the true value, and the greater the value of MSE, the greater the difference between the predicted value and the true value. It can be seen from the table that the MSE average value of the deflection results simulated by the shell element and the first-layer isoparametric element is 0.12565, and the MSE average value of the deflection results simulated by the three-layer isoparametric element is 0.03355. It can be seen that the result of shell element is closer to that of isoparametric element when simulating the deformation of faced rockfill dam. This shows that the shell element can effectively capture the mechanical properties of panel bending with a small number of grids. This is because the shell element can consider the bending characteristics of the panel and its thickness effect, and can still obtain more accurate displacement and force results of the panel under thicker mesh division.

Table 3. Mean Squared Error Values of Calculation Results

operating mode	One layer of equal reference element MSE	MSE
Check water level to river	0.138	0.021
Check the water level in the vertical direction	0.113	0.045
MSE average value	0.125	0.033

Compared with the overall structure, the panel itself is more flexible and deforms with the support system. The deformation of the vertical joint and the peripheral joint of the panel is directly related to the integrity of the water sealing system. Excessive deformation may cause the water sealing failure, and significantly affect the stress and deformation characteristics of the panel, which has an important impact on the safety of the panel structure. Therefore, it is necessary to simulate the deformation of vertical joint and peripheral joint, explore the potential impact on the water sealing effect and the safety of the panel structure, and verify the rationality of using shell elements to simulate the panel structure of concrete rockfill dam.

The deformation of vertical crack under flood level is simulated by isoparametric element and shell element of the first and third layer grids respectively. Due to the overall pouring of the panel, although the vertical joint also occurs dislocation and subsidence, the value is generally small, which is not considered here. The vertical joint tensioning displacement simulated by shell elements is shown in Figure 6, and the maximum vertical joint tensioning value simulated by different types of elements is shown in Figure 7. It can be seen from Fig. 8 and 9 that when shell element is used to simulate the tensile deformation of vertical joint by finite element method, the maximum tensile displacement of vertical joint is 17.066mm, and the overall distribution is in the state of tension in bank slope section and compression in riverbed section, which satisfies the objective law of engineering and proves that shell element can accurately simulate the deformation of vertical joint. By comparing the maximum tensile values of the simulated vertical joints of different elements, it can be seen that the simulation results of shell elements are closer to those of isoparametric elements of three-layer grid when simulating the tensile deformation of panel vertical joints.

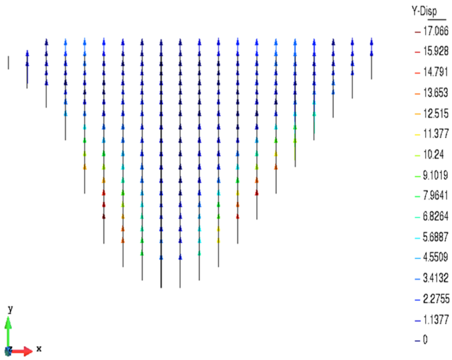


Fig. 6. Tensile Displacement Diagram of Vertical Joints Simulated by Shell Elements

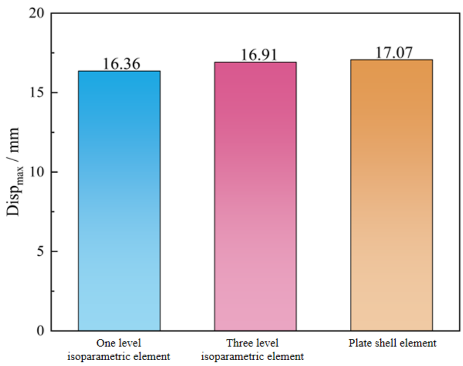
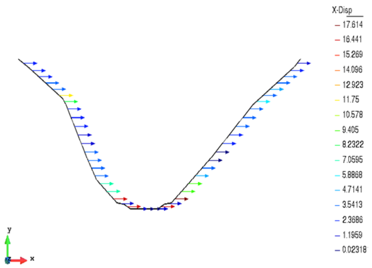
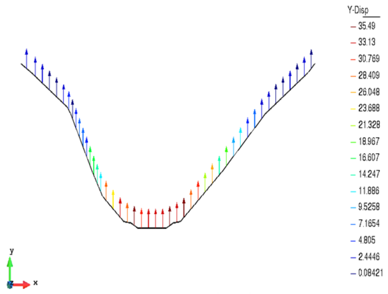


Fig. 7. Comparison of Maximum Tensile Values in Vertical Joints

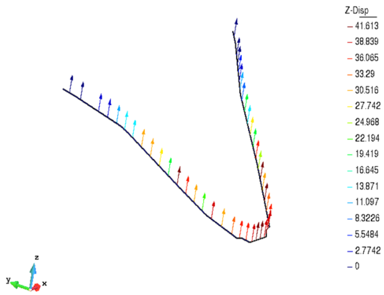
Similarly, the deformation of the peripheral joint under the checking flood level is simulated. The dislocation, tension and settlement deformation of the simulated peripheral joint by shell elements are shown in Figure 8, and the displacement of the peripheral joint along the dam axis simulated by different types of elements is shown in Figure 9. As can be seen from Figure 8 and 9, when shell elements are used to perform finite element simulation of dislocation, tension and settlement deformation of the peripheral joint, the maximum lateral dislocation displacement of the peripheral joint is 17.614mm, the maximum tension displacement is 35.49mm, and the maximum settlement displacement is 41.613mm. The overall deformation is the largest in the middle of the panel, which meets the objective laws of engineering. It is proved that the shell element can accurately simulate the deformation of the peripheral joint. By comparing the simulation results of joint dislocation, tension and settlement of different types of elements, it can be seen that the simulation results of shell element and three-layer grid isoparametric element are more similar. In summary, the shell element can effectively simulate the deformation of vertical and peripheral joints with a small number of grids.



(a) stagger

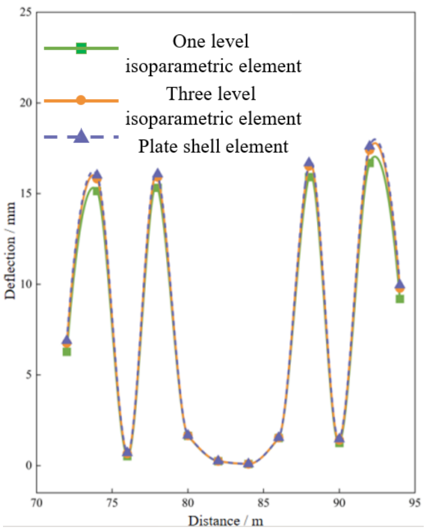


(b) tension

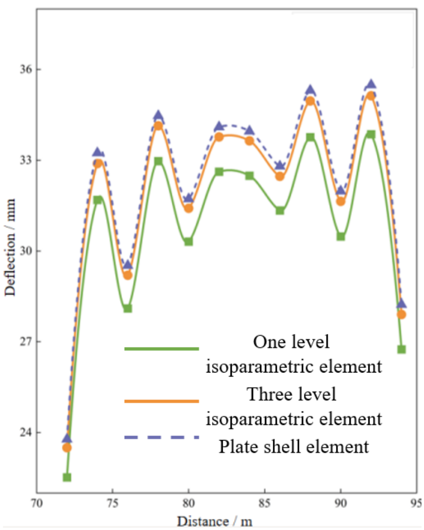


(c) sink

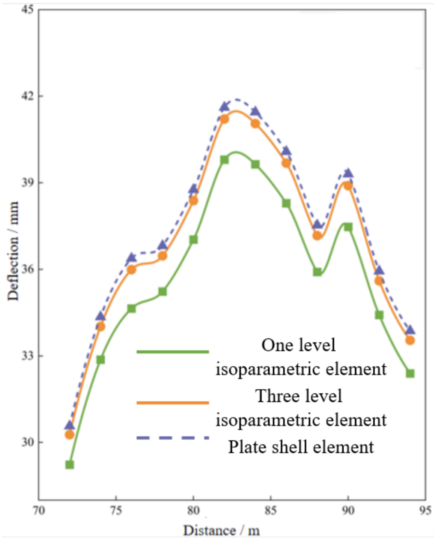
Fig. 8. Displacement Diagram of Perimeter Joints Simulated by Shell Elements



(a) stagger



(b) tension



(c) sink

Fig. 9. Comparison of Displacement in Perimeter Joints

The results of this study show that shell element can not only maintain high calculation accuracy, but also have significant advantages in calculation efficiency when simulating the face and joint of faced rockfill dam. In summary, shell elements can be further extended to the finite element calculation of faced rockfill dams to improve the accuracy and efficiency of engineering analysis, and also provide a new idea and method for the finite element analysis of similar thin plate structures.

4 Conclusion

1.Use the displacement relationship between the panel surface node and the shell unit to generate the shell unit to reduce the difficulty of model dissection and reduce the pre-processing workload;

2.The shell unit can accurately simulate the thin plate deformation, highly restore the force characteristics, significantly reduce the deviation between the simulation and the theoretical value, with accuracy and reliability;

3.In the simulation of panels and joints of panel rockfill dam, the simulation results of shell elements are closer to the precise reference elements of grid, but the number of shell elements is small and the computational efficiency is high.

Acknowledgments

Fund project: National Key RESEARCH and development Program "Rapid and accurate Diagnosis and Risk Prevention and Control of Natural Disaster damage of dam System and Auxiliary Buildings" (2022YFC3005403)

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