Finite Element Analysis of Seepage Stability of Sluice with Anti-Seepage Structure

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Abstract. In slope engineering or underground power generation tunnels and other underground projects, the control of engineering seepage is an inevitable problem in water conservancy construction. In order to study the impact of seepage on river gates, a certain river gate was selected as the research object. Establish a three-dimensional finite element model to solve the seepage field in the foundation, simulate the distribution of pore water pressure and seepage velocity in each sluice foundation, analyze the changes in pore water pressure gradient and the impact of anti-seepage measures on the seepage field, and evaluate whether the seepage amount and slope meet the stability requirements of the sluice. The results indicate that the water gate is an important component of hydraulic structures, and if leakage occurs, it will seriously affect the structural stability and safety of the water gate. The measures can effectively prevent seepage, reduce the maximum head distribution, and also take into account the structural stability of the water gate itself.

Keywords: Sluice; seepage; numerical simulation; anti-seepage wall

1 Introduction

Leakage is one of the main factors leading to the instability of water gates.[1] When the water pressure is high and the flowing water reaches a certain scale, seepage damage will occur; Common situations include piping, soil flow, contact erosion, and contact loss.[2] Due to the existence of a certain water level difference between the upstream and downstream of the water gate, the foundation soil of the water gate has a certain degree of permeability. Water flows through the gate foundation and bypasses the gate from upstream to downstream, which is not conducive to the stability of the water gate. When the seepage gradient exceeds a certain threshold, the cohesion of the soil and the slope angle, the moisture content in the soil becomes close to saturation, resulting in a considerable reduction of soil strength.[3] The seepage pressure

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caused by hydrodynamic forces causes seepage deformation of the gate foundation and the soil on both sides, leading to the rupture of the water gate.[4] Therefore, the leakage problem of the foundation of the water gate building is the main factor that causes the damage of the water gate.

There are generally two ways to take anti-seepage measures, which can be changed by grouting to improve the impermeability of the rock mass, or by using front and rear blocking and reverse filtering protection.[5] Concrete pile foundation has good impermeability, simple construction, strong bearing capacity, and low cost, making it one of the commonly used foundation treatment methods for sluice construction under complex foundation conditions.[6] Liu Wenhui conducted hydraulic energy calculations on the water gate, reflecting the effectiveness of anti-seepage by calculating the amount of leakage from the dam foundation.[7] Huang Lindan verifies the necessity of the reinforcement plan based on the structural analysis of the water gate.[8]

Previous studies have rarely considered both seepage and stress fields comprehensively, but this study considers stress analysis under seepage conditions. The anti-seepage effect of the deep overburden anti-seepage system was analyzed and studied using a three-dimensional seepage field numerical simulation system, which can reflect the water pressure in the surrounding rock and soil voids.[9] The calculation method of treating drainage hole curtains as equivalent narrow gaps takes into account numerous drainage holes, which is not only more accurate but also simplifies the calculation. Consider a mathematical model that combines the scope and shape of the seepage zone, boundary conditions, and initial conditions to form the seepage field, and study the true state of groundwater flow that is closer to it. Study the principle and effect of impermeability of concrete pile foundation, providing reference for the research of river gate engineering.

2 Theory and Method

2.1 Continuity Equation of Seepage Field

Based on Darcy's law and the law of conservation of mass, the deformation of the rock model in a saturated state can be regarded as linear elastic deformation. The continuity equation of groundwater in a stable seepage site is obtained by simulating a three-dimensional infinitesimal regular hexahedron:

$$\left[\frac{\partial(\rho v_x)}{\partial x}+\frac{\partial(\rho v_y)}{\partial y}+\frac{\partial(\rho v_z)}{\partial z}\right]dxdydz=-\frac{\partial(\rho dxdydz)}{\partial t}$$

Assuming that groundwater is an incompressible body, the continuity equation is:

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0$$

In the formula, v_x, v_y, v_z are the components in the three directions of the seepage velocity coordinate axis, ρ is the density of groundwater, t is the monitoring time.

2.2 Considering the Seepage of External Water Inflow

the seepage differential equation is:

$$\left[\frac{\partial\left(k_x \frac{\partial h}{\partial x}\right)}{\partial x} + \frac{\partial\left(k_x \frac{\partial h}{\partial x}\right)}{\partial y} + \frac{\partial\left(k_x \frac{\partial h}{\partial x}\right)}{\partial z}\right] + Q = 0$$

Considering the homogeneous rock mass, the permeability coefficient is constant, so the solution for the stable saturated seepage field is:

$$\frac{\partial}{\partial x_i}\left(k_{ij}^s \frac{\partial h}{\partial x_j}\right) - Q = 0$$

In the formula, h is the water head, k_x, k_y, k_z are the saturated seepage coefficients in the three directions of the axis respectively, k_{ij}^s is the saturation permeability coefficient tensor, Q is inflow of external water.

2.3 Theory of Seepage Stress Calculation

The changes in groundwater seepage field determine the changes in water load elements, which in turn affect the changes in stress field. This is the potential effect of seepage field on stress field. The stress state of the gate foundation determines the permeability tensor of the foundation, and at the same time, the permeability tensor affects the stress state of the foundation through the permeability volume force.[10] The interaction between the two always exists and ultimately reaches a new steady-state equilibrium.

This article considers a mathematical model for stress analysis under the action of seepage. The calculation approach is to calculate the seepage field based on the seepage parameters of the water gate, output the seepage force, and use it as the external load for the stress calculation model. Then, in the form of force, it is applied to the three-dimensional stress calculation model, considering the iteration of the load generated by the seepage head pressure and the change in strain increment of the rock and soil. Considering the stability of the water gate under the influence of seepage.

$$[K]\{H\}+\{Q\}=[S]\left\{\frac{dH}{dt}\right\}$$

$$\Delta\varepsilon_v=\frac{n\gamma}{E_W}\Delta\mathrm{H}$$

$$\{\sigma\}=[D]\left[\{\varepsilon\}+\{\Delta\varepsilon_v\}\right]$$

In the equation, $[K]$ the overall penetration matrix, $[S]$ is the water storage matrix, $\{Q\}$ arranging for external water inflow, $\{H\}$ is the water head, $\{\sigma\}$ is a stress array, $\{\varepsilon\}$ the strain matrix without considering the influence of permeability, $\{\Delta\varepsilon_v\}$ To consider the strain array of rock and soil after deformation under the influence of permeability, $[D]$ is the elastic matrix, E_W is the bulk elastic modulus of seepage groundwater, γ is the bulk density of groundwater.

2.4 Simulation Method of Seepage Boundary

Many methods are used to calculate seepage boundary in past projects. In the seepage problem with free surface, many researchers focus on the study of fixed grid method, trying to use the expanded seepage region and fixed boundary to solve the problem, so as to achieve the purpose of constant cell grid in the solution process. Various methods such as variable element permeability coefficient method, residual flow method, improved residual flow method, initial flow method, variational inequality method and cut-off negative pressure method have been produced successively. Among the above methods, the initial flow method has many advantages, such as forming and decomposing the overall conduction matrix only once, without determining the approximate position of the free surface and distinguishing the actual situation of the intersection between the free surface and the element in each iteration step. Therefore, it is a relatively effective method for solving the seepage problem with free surface with invariant mesh at present, and the above method is adopted in this study.

2.5 Simulation Method of Drainage Facilities

When the number of drainage holes is large and the range of rock mass is large, the spacing of drainage holes is very small, and then it is difficult to represent all drainage holes by pipe units, especially when some detailed structures in the analysis area need to be considered. If the actual simulation of drainage holes will make the seepage calculation extremely complicated and difficult, and it is not conducive to popularization and application. Therefore, based on the research of "replacing holes with pipes", this paper adopts "replacing Wells with fractures" to simulate the drainage holes in rock mass.

It is precisely because of its "hollow" structure that the drainage hole becomes a water conduction structure with strong permeability in the rock mass, and the drainage well series is formed by these "hollow" structures arranged in the rock mass at a certain distance to form a strong water conduction hole screen. The surrounding groundwater flows into the drainage hole screen and drains along the hole wall under the hydraulic gradient. The formation of a zonal distribution of seepage depressurization zone in the rock mass is just like a narrow gap or a narrow ditch in the rock mass from a macroscopic perspective.

According to the macroscopic method of percolation theory, from the structure of permeating medium and characteristics of percolation field, the drainage hole screen can be regarded as an equivalent narrow slit, that is, "replacing well rows with cracks", and on the basis of meeting the principle of the equivalent seepage flow and water head, the corresponding equivalent permeability coefficient of the narrow slit can be assigned.

2.6 Transformation and Solution of Mathematical Model

Firstly, the scope of the study area and the boundary of the seepage zone are determined according to the topographic and geological conditions, and the hydraulic characteristics of the seepage zone are determined according to the hydrogeological conditions, including burial conditions, seepage state and medium characteristics. A reasonable differential equation is selected to represent the flow law of groundwater, and the boundary conditions and initial conditions indicate the specific environmental conditions of the object of study, that is, the real state of the groundwater flow studied.

3 Calculation of Seepage Stability of Levee

3.1 Finite Element Model

The large three-dimensional seepage calculation model of sluice is established. The global coordinate system is based on the center of the middle gate hole on the gate axis. In the X direction, the upstream direction is 120.0m, and the downstream direction is 220.0m. The Y direction is positive with the vertical river pointing to the left bank, 100.0m to the right and 100.0m to the left; The Z direction is straight up to be positive, and the upward orientation is 50.0m down.

The overall model size is 340m×200m×50m. Hexahedral 8-node elements were used to divide the grid of the model. The grid of the calculation model is shown in Figure 1. According to the contour lines of the dam body and foundation, the surface area is divided and the material properties of the model are defined. The finite element mesh is divided using unstructured quadrilateral and triangular meshes, and the aspect ratio of the elements is controlled between 1:1.0 and 1:1.2. The calculation model takes the normal water retaining work condition of the water gate bottom plate elevation of 21.41 as an example, with the X direction being the same as the 3D model, and the Y direction being positive in a vertical upward direction. The model is shown in Figure 2.

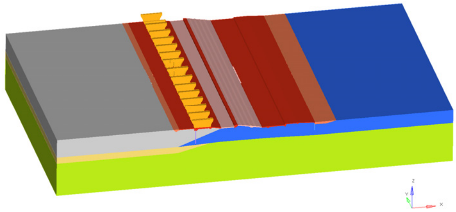

Fig. 1. Three-dimensional finite element model for seepage calculation of sluice

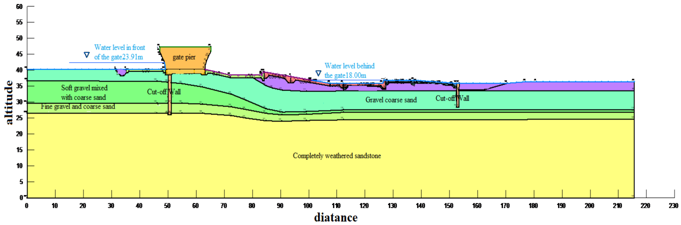

Fig. 2. Normal water retaining working condition model

3.2 Boundary Conditions and Material Parameters

The stable seepage field formed by the seepage flow of the sluice base and the seepage flow around the dam is calculated. The boundary between the two sides of the seepage simulation area and the bottom of the foundation is defined as the water boundary. The surface, downstream and water contact plane of the foundation are subjected to water load, which is defined as the water head boundary. The calculation boundary condition is as follows: the upstream water head is known: H1=2.50m, and the downstream water head is known: H2=1.00m. The floor elevation is 21.41m. Table 1 lists the material parameters of each part.

Table 1. Seepage calculation parameters of sluice

item	Heavy(KN /m^3)	elastic modulus(MPa)	Poisson's ratio	C_k(KPa)	φ (°)	permeability coefficient K_H(m/s)	pore ratio
C30	25.0	3.0×10^4	0.167	-	-	5.0×10^{-10}	0.305
Concrete cutoff wall	24.0	2.2×10^4	0.167	-	-	5.0×10^{-8}	0.305
Medium and	21.1	12.0	0.25	0	26	5.36×10^{-3}	0.339

coarse sand							
Coarse, gravel sand	22.0	15.0	0.20	0	33	2.19×10^{-1}	0.300
Eluvial soil	19.1	30	0.24	22.6	21.2	2.56×10^{-5}	0.754
Argillaceous siltstone	19.9	1280	0.3	27.9	24.1	4.36×10^{-5}	0.605
Hand fill	1980	5.09	0.25	15.1	16.7	4.17×10^{-5}	0.500

3.3 Pore Water Pressure Situation

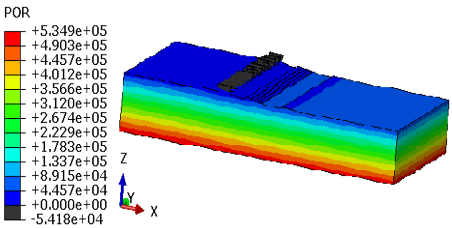

Fig. 3. Isoline map of overall pore water pressure of sluice(Pa)

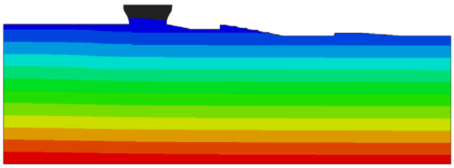

Fig. 4. Enlarged map of pore water pressure contour in sluice control section

The above boundary conditions and material parameters are given to the model for calculation, and the distribution of the seepage field of the sluice is calculated. See Figure 3 and Figure 4 for the flow field of the three-dimensional sluice calculation model of the dam.

It can be clearly seen that the water pressure on the upstream side is higher than that on the downstream side, and the groundwater in the foundation decreases along the direction of the downstream flow. Among them, the upstream side water pressure is 24525Pa, and the downstream side water pressure is 9810Pa.The location of groundwater buckling in the foundation is the location of the upstream and downstream anti-seepage walls. It can be seen that the installation of anti-seepage walls has a positive effect on the anti-seepage of sluice foundation.

Concrete anti-seepage wall is set under the upstream blanket and anti-filtration drainage layer is set under the underside of the gate. The anti-seepage system of cement curtain grouting is adopted around the dam at both sides. Through the three-dimensional seepage field numerical simulation of the dam and the foundation, the arrangement of the anti-seepage system combining vertical anti-seepage with horizontal anti-seepage, drainage and water filtration measures on the surface is reasonable and feasible. It is very effective to reduce the seepage pressure of gate foundation, control seepage around dam and ensure the stability of foundation seepage.

3.4 Total Head Condition

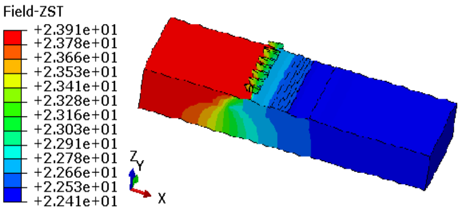

Fig. 5. Isoline map of total head of sluice

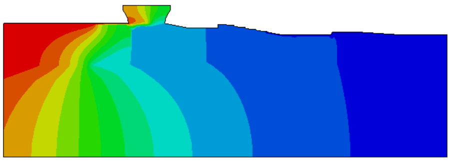

Fig. 6. Enlarged contour map of total head of sluice control section

In order to visually observe the position of the total head line of the foundation of the sluice, the calculation results of the seepage field were post-processed, and the middle section of the sluice was intercepted for head analysis. The distribution diagram of the head line of the river gate and dam was shown in Figure 5 and Figure 6.

It can be clearly seen that the total water head upstream of the sluice foundation is 23.91m, and the total water head downstream is 22.41m. The overall total water head is high upstream and low downstream in the downstream direction of the downstream flow, which conforms to the actual situation of high upstream water level and low downstream water level under the established working conditions of the sluice. The overall trend of free underground water surface decreasing along the way is consistent with the equipotential line perpendicular to the flow line. The water head forms a collection at the bottom of the gate, the intersection of different foundation covers and the location of the cutoff wall.

It is also worth noting that the total water head line is obviously bent at the intersection of different foundation cover layers and the position of upstream and downstream cutoff walls. The results show that the seepage effect of different foundation covers on groundwater is different, and the anti-seepage wall can reduce the foundation water head to a certain extent, and has a positive effect on the anti-seepage of sluice foundation.

3.5 Velocity Condition

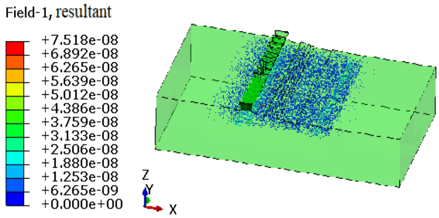

Fig. 7. The overall flow rate of the sluice(m/s)

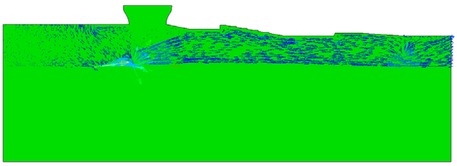

Fig. 8. Enlarged view of flow rate in sluice control section

In order to analyze the flow velocity of the sluice foundation under the condition of recommended scheme 1, the calculation results of the seepage field are post-processed, and the middle section of the sluice is intercepted for head analysis. The distribution diagram of the head lines of the sluice and dam is shown in Figure 7 and Figure 8 above.

It can be concluded that the seepage flow is blocked at the upstream and downstream positions of the seepage prevention wall, and the direction of the water flow first goes down the seepage prevention wall, turns sharply horizontally when it reaches the bottom of the seepage prevention wall, and then points downstream along the direction of the foundation covering layer. Therefore, the flow velocity of the groundwater at the bottom of the seepage prevention wall reaches the maximum, and the maximum flow velocity is 7.52×10-8m/s.

In addition, it can be seen from the three-dimensional flow rate diagram that the permeability coefficient of the lowest base cover layer is very different from that of the upper foundation cover layer. The upper layer is a strong permeable layer, while the lower layer is a weak permeable layer. The flow line is gentle in the homogeneous foundation cover layer.

3.6 Infiltration Gradient

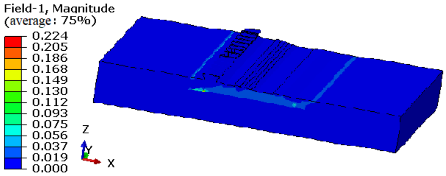

Fig. 9. Overall infiltration slope of sluice

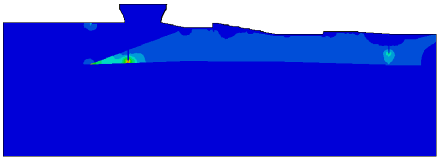

Fig. 10. Enlarged view of infiltration gradient in sluice control section

In order to analyze the seepage slope of the sluice foundation under the condition of recommended scheme 1, the calculation results of the seepage field are post-processed, and the middle section of the sluice is intercepted for water head analysis. The distribution diagram of the seepage slope results of the sluice dam is shown in Figure 9 and Figure 10 above.

It can be seen that the maximum hydraulic gradient of the control section of the lock chamber reaches 0.224, which is located at the bottom of the upstream cutoff wall. This is because the seepage water flow is blocked, the direction of the upstream position of the anti-seepage wall is down along the anti-seepage wall, and the water flow turns sharply in the horizontal direction when it reaches the bottom of the anti-seepage wall, resulting in the seepage slope of the anti-seepage wall. According to Darcy's law, the permeability gradient value is the ratio of flow velocity to permeability coefficient, and it is concluded that the permeability gradient at the bottom of the upstream cutoff wall is the largest. In addition, at the intersection of foundation cover layers with different properties, the permeability coefficient also changes, so the corresponding position of the permeability gradient increases, among which the upper layer of the lock, the coarse sand cover layer and the coarse and gravel sand cover layer also has an increase in the permeability gradient, reaching 0.186, meeting the standard of the lock.

4 Calculation Result Analysis

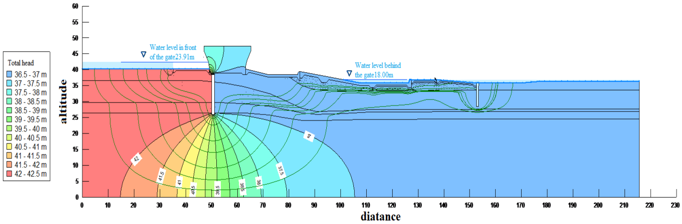

Fig. 11. Contour map of total water head at normal storage level(m)

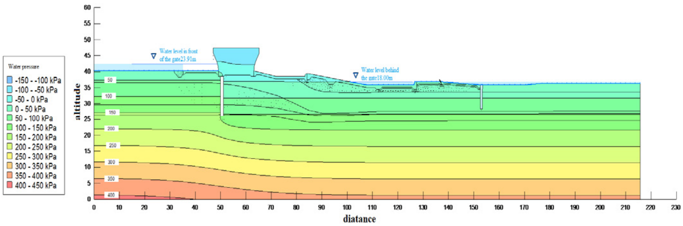

Fig. 12. Contour map of normal water level water pressure(KPa)

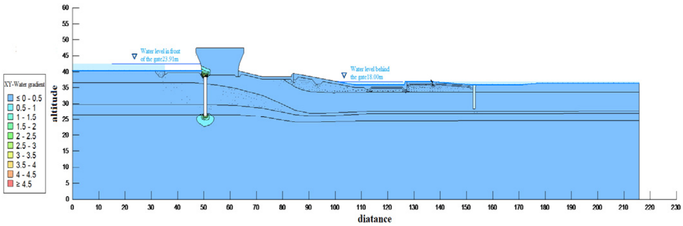

Fig. 13. Contour map of normal water level infiltration slope

Figures 11-13 show the total head contour map, water pressure contour map, seepage gradient contour line map of the 21.41m sluice bottom slab under normal storage water level conditions, further demonstrating the anti-seepage effect of the anti-seepage wall, with each index far less than the allowable breaking value.

(1) According to the calculation results, the permeability gradient at the downstream cutoff wall of the sluice gate with the floor elevation of 21.41 meters is less than the allowable value. At the normal storage level, the local permeability gradient of the upstream cutoff wall is larger than that of the downstream cutoff wall, ranging from 0 to 4.5. The infiltration slope after the gate is small, and no infiltration damage will occur. It can be seen from the escape ratio drop of the infiltration line that both

the potential and the infiltration slope are far less than the allowable value when the soil in the corresponding part of the model material is damaged. The outflow ratio is very small and the seepage flow rate is also very small, indicating that the seepage state is relatively stable.

(2) The flow line under the normal storage water level is bypassed under the upstream cutoff wall, bypassed the rear cutoff wall along the soil layer from below, and reached the downstream soil surface. Only a small part of the seepage flows out of the soil surface through the stilling pool. The water level and potential of the sluice in this section decrease gradually from upstream to downstream, which accords with the general law of seepage. The water level and potential in front of the anti-seepage wall are higher, and the difference between the water level at the bottom of the sluice gate behind the anti-seepage wall and the water level in front of the sluice gate is about 3~4 meters under the normal storage water level, indicating that the anti-seepage curtain has a good anti-seepage effect. After that, the water level potential has no obvious upward or downward trend, and the soil seepage is basically stable.

(3) Under normal storage conditions, the single wide flow rate through the anti-seepage wall in front of the gate is $1.59\times10^{-7}m^3/s$, and the single wide flow rate through the section behind the gate is $8.61\times10^{-8}m^3/s$, and the seepage rate is small, which is a stable seepage.

5 Conclusions

(1) According to the calculation results of seepage flow in the sluice area, the groundwater in the sluice foundation decreases along the downstream flow direction, and the flow line is skewed at the upstream and downstream cutoff walls. In the direction perpendicular to the water flow, the center line of the river channel is taken as a reference, and the groundwater flow line tends to decrease along the left and right banks. The flow line is skewed at the cut-off wall in the slope area, which verifies the effectiveness of the cut-off wall. Moreover, the flow rate of groundwater at the bottom of the cutoff wall reaches the maximum, and the maximum flow rate is $7.52\times10^{-8}m/s$.

(2) The water pressure on the upstream side of the foundation of the sluice chamber section is 24525Pa, and the water pressure on the downstream side is 9810Pa. The total water head of the upstream is higher in the upstream direction and lower in the downstream direction, which accords with the established situation of the downward trend of the free groundwater surface. The equipotential line is perpendicular to the flow line, and the water head gathers at the bottom of the gate, the intersection of different foundation cover layers and the position of the cutoff wall. The cutoff wall can reduce the foundation water head to a certain extent.

(3) The maximum hydraulic gradient of the sluice control section reaches 0.224, which occurs at the bottom of the upstream cutoff wall. In addition, there is also an increase of seepage gradient in the middle, coarse sand cover layer and coarse and gravel cover layer of the sluice upper layer. Up to 0.186, all in line with the standard requirements.

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