Stability Analysis of the Scour Funnel in front of the Flood and Sediment Discharge Tunnel of the Guanting Reservoir

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Abstract: Guanting Reservoir is the first large reservoir building in the Early PRC, and undertakes the important mission to flood-control, irrigation, water supply for industry and city, hrdroelecity and so on, and it is also one of the important sources of water supply of Beijing, Capital of China. This thesis analyzes the formation process and status of the scour funnel in front of the flood and sediment discharge tunnel, and mainly studies the stability of the scour funnel.

Key words: Guanting Reservoir, the Scour Funnel, the Flood and Sediment Discharge Tunnel, Stability Analysis

1 Formation Process of the Scour Funnel

The deposition form of the reservoir is closely related to the operational mode of the reservoir and the incoming runoff and sediment load. Since 1953, the operation modes of Guanting Reservoir are as following Form 1; the eigenvalues of the incoming runoff and sediment Load is as following Form 2; the developing process of the reservoir deposition is as following Picture 1.

Form 1: Operation Modes of Guanting Reservoir

Periods	Operation Modes	The Average Water-level during the Flood-season （m）	The Highest Water-level before the Flood-season （m）
1953.6~ 1955.10	Flood Detention	456.06	466.16
1955.10~ 1974.5	Water Storing	473.5	478.62
1974.6~ 1980.5	Water Storing	473.76	478.83
1980.6~ 1990.5	Water Storing	473.66	475.94
1990.5~ 1997.6	Water Storing	475.27	478.5
1997.1~ 2004.12	Water Storing	473.65	474.36
1955.10~ 2004.12	Average Value	473.97	477.25
Note: the data before June 1997 are from Reference [1]			

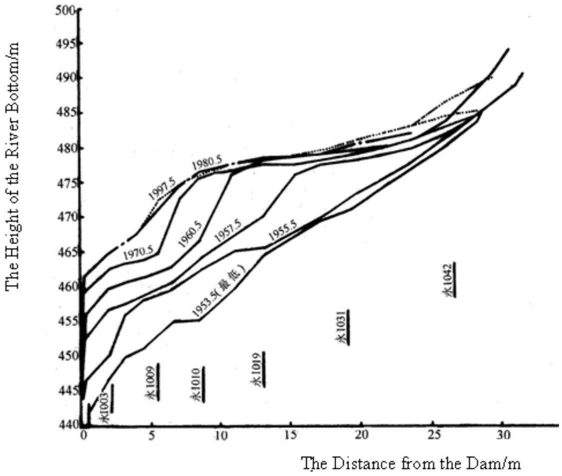
Form 2: Eigenvalues of the Incoming Runoff and Sediment Load of the Guanting Reservoir

Periods （Year）	Incoming Runoff		Incoming Sediment Load （Million t）
	Yearly Runoff （Billion m^3）	Ratio between Flood-season and Year（%）	
1953~1959	1.954	54.66	70.41
1960~1969	1.286	43.57	16.33
1970~1979	0.841	45.71	10.77
1980~1989	0.502	43.53	4.07
1990~2000	0.359	47.33	3.07
2001~2004	0.132	23.48	0.51
Note: the data before 2000 are from Reference [1]			

From these forms and picture 1,

（1）Before Oct. 1955, the reservoir was mainly for the flood detention, and the water-lever during the flood-season was low, the incoming sediment was mainly deposited between the dam and Section No. 1019 with the form of cone.

（2）From Oct. 1955, the reservoir started to store water. The water-level during the flood-season was high and stable. The sediment was deposited with the form of triangle. Only part of fine sediment carried by the density stream was deposited in front of the dam. Therefore, the deposition of Section No.1000 was non-uniform from 1955 to 2004. Only during the years of plenty of runoff and sediment, the density stream happened more often, the fine sediment deposited more in front of the dam.



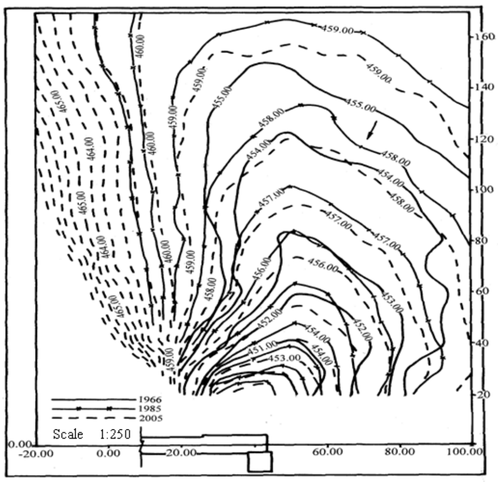
Picture 1: Developing Process of the Guanting Reservoir Deposition

For example, from May 1955 to May 1957, the height of Section No.1000 uplifted from 446.5 to 453.3 m, with 3.4m per year; while from May 1960 to May 1970, the height of Section No.1000 uplifted from 454.5 to 457.5 m, with only 0.3m per year. The reason of above phenomena is mainly that, during 1955 and 1956 there comes plenty of runoff and sediment; especially in 1956, the yearly incoming runoff is 2.21 billion m^3, 2.42 times that of the average runoff between 1953 and 2000; at the same time, the yearly incoming sediment load is 77.60 million t, 4.44 times that of the average between 1953 and 2000. Otherwise, during the majority of years between 1960 and 1970, the density stream happened seldom, so the section height uplifted less. What's more, from May 1980 to May 1997, the height of section in front of the dam hardly changed, that is mainly because the incoming runoff and sediment load decreased greatly (From 2).

2 The Status of the Scour Funnel

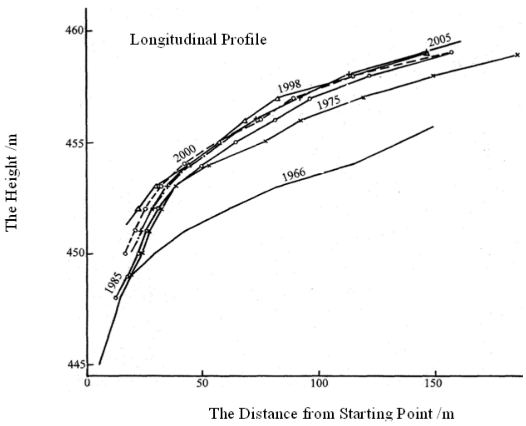
Partial topographic map in front of the flood and sediment discharge tunnel of Guanting Reservoir during some typical years is as flowing Picture 2, the longitudinal profile and cross section in front of the flood and sediment discharge tunnel of Guanting Reservoir during some typical years are respectively as flowing Picture 3 and Picture 4 (the section locates left and 25m up of the intake).

From these pictures, because of the influence of the right bank, the direction of the main-stream of the scour funnel in front of the flood and sediment discharge tunnel is not vertical to the tunnel, with an angle of 20^0 between direction of the main-stream and the tunnel. Experiment [2] results show, the planform of the scour funnel in front of the bottom orifice looks like half-ellipse. Now forms a scour funnel with the length of 250m and the breadth of 120m and the depth of 17m.

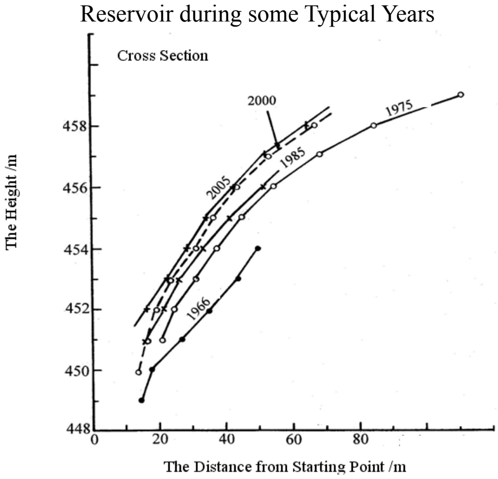


Picture 2: Partial Topographic Map in front of the Flood and Sediment Discharge Tunnel of Guanting Reservoir during some Typical Tears

From Picture 2, the scour funnel had mainly formed before the 1980s. Since the 1980s, because of the great decrease of the incoming runoff and sediment load, the scour funnel has developed slowly. Such as the contour line of 455m, from 1966 to 1985, it advanced about 136m along the direction of the main-stream, about 7.2m per year; otherwise, from 1985 to 2005, the contour line of 455m only advanced 7m, about 0.35m per year.



Picture 3: Longitudinal Profile in front of the Flood and Sediment Discharge Tunnel of Guanting Reservoir during some Typical Years



Picture 4: Cross Section in front of the Flood and Sediment Discharge Tunnel of Guanting Reservoir during some Typical Years

From Picture 3, the slope of the longitudinal profile with the rang of 40m from the intake is quite steep, about 17%; the slope between 40 and 150m is about 4%; the slope farther than 150m is flatter.

From Picture 4, the slope of the cross section in 35m from the centerline is quite steep, about 22%; the slope between 35 and 115m is about 4%; the slope farther than 150m is flatter.

Like as the other reservoirs [3], the slope of the cross section is larger than that of the longitudinal profile. That is mainly because the main-stream trend is from single-direction open-channel flow to orifice conflux. The velocity and unit-width discharge are non-uniform along the stream and lateral orientation, and generally, the former is lager than the later, and he difference is more obvious along with the increase of the discharge, which induces that the coefficient of the longitudinal slope is smaller than that of the lateral.

3 The Stability Analysis of the Scour Funnel in front of the Flood and Sediment Discharge Tunnel

Based on stress conditions of the sediment particle, the function relationship between and slope coefficient (m) of the scour funnel and factors of water and sediment can be conduced as following [3]:

$$m = f'\left(\frac{Qu_1}{u_c^2 Z^2}, \frac{D_1^2}{H_c^2}, \overline{C}, \tan\varphi\right) \qquad \ldots(1)$$

Q is the orifice runoff（m^3/s）; u_1 is the average orifice velocity（m/s）; u_c is the velocity of sediment incipient motion（m/s）; Z is the deposition depth in front of brake（m）; D_1 is the orifice dimension（m）;

H_c is the water depth in front of the brake; $\overline{C}$ is the inner cohesion power of the sediment particles; tanφ is the friction coefficient between sediment and river-bed, denoted by the internal friction angle or the repose angle.

The above function can be used to analyze the stability of the slope. From above function, it is obvious that, the factors which influence the stability of the slope mainly include hydrodynamic conditions (such as water depth in front of the orifice, the orifice runoff, the velocity distributing in front of the orifice, and so on) and physical characters (particle size distribution, the velocity of sediment incipient motion, the inner cohesion power of the sediment particles, internal friction angle, and so on). For the Guanting Reservoir, D_1 and Z can be thought as the constant.

3.1 The water depth in front of the dam and the runoff discharge

From Oct. 1955, the water-level during the flood-season always remained high. From the Form 2, the average water-level during the flood-season was 473.97m, about 30.2m higher than the intake height of the flood and sediment tunnel.

Some research results show [1,3], for the Guanting Reservoir using for storing water, and always keeping backwater in front of the brake, and H/h (H is the water depth in front of brake, and h is the height of orifice)or B/b (B is the river width in front of the brake, and b is the width of the orifice)remaining large, the slope of the scour funnel is steep; if the runoff discharge is small, the slope remains stable and is close to the repose angle; if the runoff discharge is large, the water level decreases gradually, H/h and B/b decrease and trend to 1, and the slope of the scour funnel decrease correspondingly.

During the course of the decrease of the water-level, as long as the reservoir remains backwater, that is, the water-level in front of the dam is higher than the normal water-level of the river, and if this, both the longitudinal and the lateral slope change little. Only if the water-drop happens, the slope may decrease.

Experiment results [4] show, when the water-level in front of the reservoir remains 468m, the slope with the range of 40m is 20.45%,; the slope from 40m to 70m is 11.57%; the slope from 70m to 130m is 4.9%. When the water-level in front of the reservoir remains 481.25m, the slope with the range of 40m is 21.3%,; the slope from 40m to 70m is 8.2%; the slope from 70m to 100m is 5.1%.

The main reason that the slope of the reservoir remains stable is that the reservoir always remains backwater.

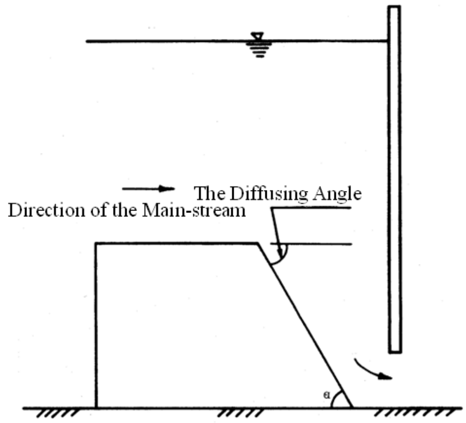
3.2 The runoff discharge

Experiment results [4] show, at the same water-level of 471.47m, when the runoff discharge are respectively 100m^3/s、300 m^3/s and 473 m^3/s, the larger runoff discharge, the larger the dimension of the scour funnel, yet the slope of the scour funnel changes little (Form 3).

Form 3: Eigenvalues of the Scour Funnel in front of the Flood and Sediment Tunnel under the Conditions of the Different Discharge

The Runoff Discharge(m^3/s)	100		300		473	
Distance (m)	0	40	0	40	0	40
Height (m)	444.9	453.42	443.99	452.85	443.86	453.16
Slope (%)	21.3		22.15		23.25	

In a word, as long as the reservoir remains backwater, the reservoir water-level and the runoff discharge have little influence on the scour funnel. Besides the small runoff discharge of the flood and sediment discharge tunnel, the other important factor to the stability of the slope is the stream configuration in front of the scour funnel. When the reservoir remains backwater, the cross section in front of the scour funnel enlarges abruptly (Picture 5). The inertia of the stream makes the borderline separate. The velocity of the upper main-stream decreases alone the distance, and the pressure increase alone the distance, so the circumfluence forms under the borderline, which prevent the slide of the sediment on the scour funnel, and therefore, the slope remains stable.

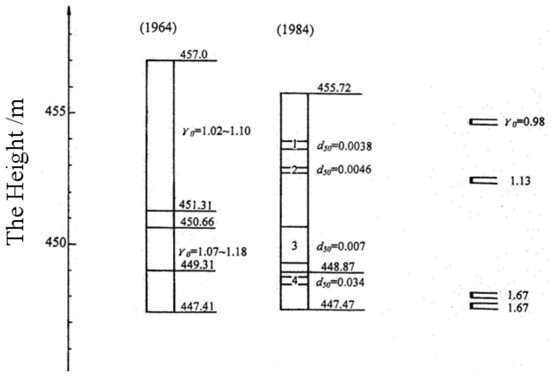


Picture 5 the Sketch Picture of the Separating of Stream Borderline of the Scour Funnel

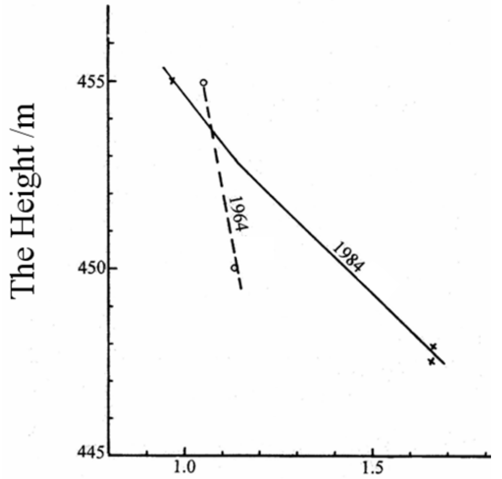
3.3 Physical Character of the Sediment in front of the Dam

During the different using phases, the physical character of the sediment is also different. Before Oct. 1955, the reservoir was used for flood detention, and the incoming sediment was mainly deposited between the dam and Section No. 1019 with the form of cone. Particle sizes and the dry bulk density of the sediment were large. From Oct. 1955 to Oct. 2005, the reservoir started to store water. The water-level during the flood-season was high and stable. The sediment was deposited with the form of triangle. Particle sizes and the dry bulk density of the sediment were smaller than that before Oct. 1955.

Samples column distribution of the sediment in front of the Guanting Dam in 1964 and 1984 is as following Picture 6. From Picture 6, the dry bulk density of the sediment increases along the depth of the drill from 1t/m^3 to 1.67t/m^3, which reflects the influence of the deposition depth to the dry bulk density. On the other hand, along with time going, the concretion degree increases.



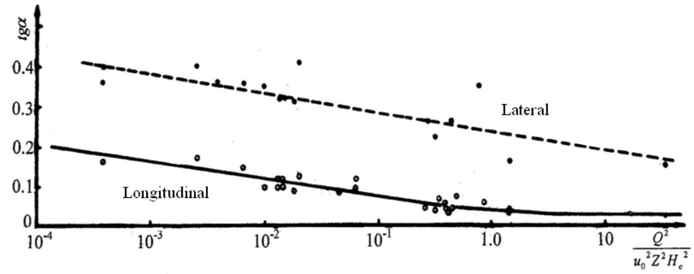
Picture 6: Samples Column Distribution of the Picture Sediment in front of the Guanting Dam in 1964 and 1984



Picture 7: Linear Relationship between the Dry Bulk Density and the Drill Depth

Under the assumption of linear relationship between the dry bulk density and the drill depth, the relationship between them is as following Picture 7. From Picture 7, 20 years later, at the height of 450m, the dry bulk density increased by 22%, from1.11 t/m^3 in 1964 to 1.35t/m^3 in 1984.

Based on the observed data of the topography and incoming runoff and sediment, relationship between slope of the scour funnel and the factors of the incoming runoff and sediment is as following Picture 8 [3]. From Picture 8, the longitudinal slope can be divided into 3 classes. The slope of the deep layer is steep; the slope of the middle layer is gentle; the slope of the surface layer is quite equal to the equilibrium river slope of transporting sediment in long distance.



Picture 8: Relationship between Slope of the Scour Funnel and Factors of the Incoming Runoff and Sediment

From the function $\eta = \frac{Q^2}{u_c^2 Z^2 H_c^2}$, Z can be thought as the constant, and H_c and Q have little influence to the slope, so u_c is the key influence factor of the slope. When d_{50} is equal to 0.015mm and H is equal to 30.2m, based on Zhang Ruijin Formula:

$$U_c = \left(\frac{h}{D}\right)^{0.14}\left(17.6\frac{\gamma_s-\gamma}{\gamma}D + 6.05\times10^{-7}\frac{10+h}{D^{0.72}}\right)^{\frac{1}{2}} \quad \ldots(2)$$

u_c is about equal to 0.065m/s, and $\eta = \frac{Q^2}{u_c^2 Z^2 H_c^2}$ is about 0.59. Based on Picture 8, m is about equal to 0.05-0.06, larger than 0.04 (the second class slope of the scour funnel in Picture 4), which indicates that the slope is stable.

What's more, considering the influence of the compressing consolidation, the slope is more stable. When d_{50} is equal to 0.01mm, and H is equal to 20m, and the dry bulk density is equal to 1.1t/m^3, based on Han Qiwei Formula:

$$V_{b,k}^2(d) = 27.41\frac{\gamma_s-\gamma}{\gamma}d + \frac{0.1561\times10^{-7}}{d}\left(3-\frac{t}{\delta_1}\right)\left(\frac{\delta_1^2}{t^2}-1\right) + 1.301\times10^{-7}\left(1-\frac{t}{\delta_1}\right)\left(3-\frac{t}{\delta_1}\right)\frac{H}{d} \quad \ldots(3)$$

$$t = \begin{cases} t' & (t' \le 0.8\delta_1) \\ \dfrac{t'}{0.273 + 0.909\dfrac{t'}{\delta_1}} & (0.8\delta_1 < t' \le 3\delta_1) \end{cases} \quad \ldots.(4)$$

$$\gamma_s' = \begin{cases} \left[0.698 - 0.175\left(\dfrac{t}{\delta_1}\right)^{\frac{1}{3}\left(1-\frac{t}{\delta_1}\right)}\right]\left(\dfrac{d}{d+2t}\right)^3\gamma_s & (t' \le 0.8\delta_1) \\ 0.526\left(\dfrac{d}{d+2t}\right)^3\gamma_s & (0.8\delta_1 < t' \le 3\delta_1) \end{cases} \quad \ldots(5)$$

u_c is equal to 0.07m/s; when the dry bulk density is equal to 1.27t/m^3, u_c is equal to 1.96m/s, and η is equal to 6.4×10^{-4}, m is about 0.18. Furthermore, after another 20 years, the dry bulk density is larger than

1.27t/m^3, and the m is larger 0.18, so the slope is more stable.

4 Conclusions

(1) The scour funnel in front of the flood and sediment discharge tunnel of the Guanting Reservoir, mainly formed before 1980s, and after the 1980s, the conformation of the scour funnel changed little because of the great decrease of the incoming runoff and sediment.

(2) The slope of the longitudinal profile with the rang of 40m from the intake is quite steep, about 17%; the slope between 40 and 150m is about 4%; the slope farther than 150m is flatter.

(3) The factors which influence the stability of the slope mainly include hydrodynamic conditions and physical characters.

(4) In a word, as long as the reservoir remains backwater, the reservoir water-level and the runoff discharge have little influence on the scour funnel.

(5) The velocity of sediment incipient motion u_c is the key influence factor of the slope.

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