**Analysis of the One Reservoir Dam Breach Cause and the Repair Design**

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**Abstract**: The right vice-dam of the One Reservoir in Qinghai Province breached on the morning of April 28th,2005. In order to thoroughly investigate the cause of the dam breach and collect data for the coming reconstruction, analyses are made on the non-uniformity deformation, seepage characteristic, anti-sliding stability under the circumstance of earthquake, based on the original design and construction data of the dam. Conclusion is that the cracks between the bottom and two sides of the spillway and the dam body, and the subsequent seepage compounded by the earthquake, are the main factors behind the dam breach. Based on the above analyses, the repair design of the breached dam section is presented, including the selection of the repair plan of spillway based on topography and geological research and the plan of the repair of the collapsed dam section and the reconstruction the spillway.

**Key Words:** Dam Breach, Repair Design, Spillway of the Dam, One Reservoir

Fig.1 the Location of One Reservoir

The collapse of right vice-dam of One Reservoir on the morning of April 28th, 2005 is a direct result of the breach of the spillway on the dam. The reservoir is located in the lower reaches of the One River in Dulan County, Qinghai Province, 2km away from the One Gully mouth, and 15km from the one sheep pasture and 20km from Dulan Town. In this paper the cause of the dam breach is explored and analyzed, and the repair design is presented, based on on-the-spot inspection and indoor/outdoor tests.

## 1 the Breach of the Dam

There was heavy snow in this area in the spring of 2005 and heavy snow collected. Meanwhile, the following warm weather melted the ice and collected snow. To reduce the input of flood because of melted-snow water the input gate was closed on April 6th.On April 16th, the water elevation of the reservoir reached as high as 3320.80m (normal reservoir storage water level 3320.91m, the elevation of the spillway bottom 3319.40m); while April 27th 3320.27m. But at 8-9 o’clock that day, there was a sudden increase of water, and at 22 in the evening flushing gate was open to let water out Almost at the same time there was an earth quake measuring　4.2 on the Ms scale in the junction of Wulan county and Dulan county in Haixi region (north latitude 36.7°, east longitude 98.4°). At 0:07 April 28th, another earthquake measuring 3.8 on the Ms scale erupted (north latitude36.6°, east longitude 98.1°), with its epicenter only 60-70km away from the reservoir.

The spillway was normal till 1 o’clock April 28th. At 3:30 a water flow, with a diameter of 20cm, was detected on the right slope of the spillway lower reaches, and the elevation of the seepage spot was about 3317.80m. So the reservoir workers opened the spillway gate to let water out, even so, the seepage water's diameter increased to 60cm within 5-6minutes.And whirlpool with about 3318.80m elevation was detected in the left upper reaches of the spillway (see fig.2). At 4:40 the lower reaches of the spillway began to collapse, and at about 5:40 a scouring cut off 3m size appeared on the right side of the spillway top. Seepage water gained momentum and the dam body below the spillway was emptied by the scouring water. At about 6:20 the whole right spillway was breached, with its scouring cut more than 20m wide.

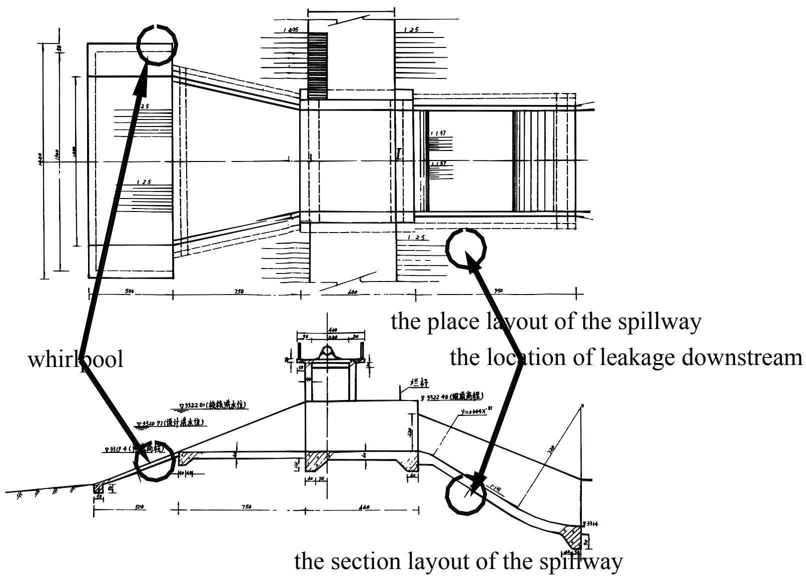



Fig.2 The location of the seepage spot and the whirlpool

After the breach of the dam, the spillway was completely destroyed, and the 9 reinforced piles, once forming the foundation of the spillway gate, were flushed down .A scouring cut, 51.65mwide and 15.0m deep appeared. Besides destroying the dam body, the scouring reservoir water cut about 10m deep into the dam base, from the alluvial soil stratum, to the sand stratum and to the gravel stratum, creating an 8m-10m high erosion slope on the upper reaches of the dam slope. After the formation of the big cut, a stretched crack developed on the right dam body. in the lower reaches, the crack was 1cm-2cm wide, 2.3m-2.5m below the collapsed surface ,and in the upper reaches the crack was 2cm-18cm wide,1.3m-2.0m below the collapsed surface.4-5 cracks developed on the left dam, with the greatest stretched one, in the lower reaches, 4cm-26cm wide, 2.3m below the collapsed surface, while in the upper reaches, 10cm-15cm,3.8m below the collapsed surface. The upper dam slope was totally collapsed.

## 2 Deformation calculation and analysis

Seen from the section layout of the former spillway, the spillway on the dam body was of rigid structure, or reinforced concrete structure; the dam body below the spillway was of flexible structure. So the spillway foundation settlement and the pile foundation settlement consisted of the calculation of settlement. Based on geological survey and through layer wise summation method, a conclusion is drew that the final settlement of the dam body below the spillway was 0.224m.But the actual settlement of the gate bottom was little because it was jacked by the reinforced piles based on the sand-gravel stratum .So at the gate bottom appeared level cracks and then at the junction of the dam body and the spillway's gate and wing wall also appeared cracks.

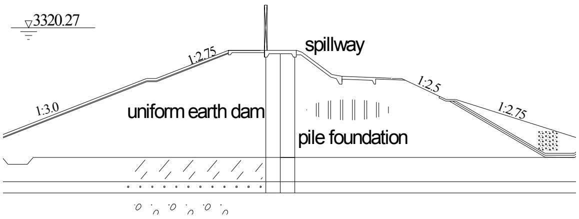



Figure 3 Spillway section

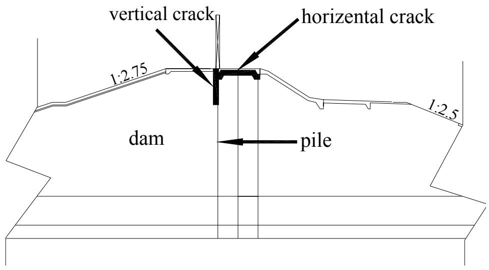



Figure 4 The location of cracks

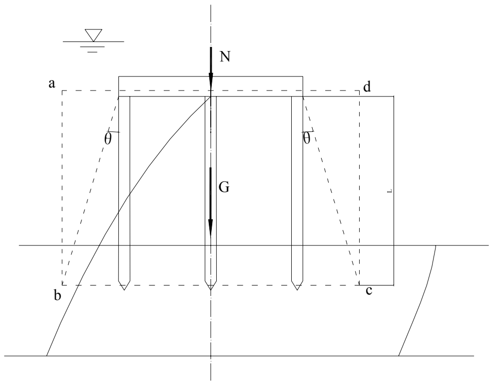



Figure 5 Diagram of the pile foundation

The foundation of the spillway gate bottom is made of 9 reinforced piles. That is, the spillway bottom has a pile foundation. The calculation diagram is illustrated in figure 5.The settlement of the pile foundation is 0.025m through calculation of settlement of the soil in the compacted layer below the pile-end surface, based on even load on rectangular foundation theory. So there was a bout 20cm crack between the gate bottom and the dam body below, and that is the location of the seepage contact. Seen from the section layout of the former spillway (see fig.3), nine concrete piles formed the pile foundation of the spillway bottom, based on the sand-gravel stratum. A conclusion can be made that pile load is mainly the function of pile friction according to the design and layout of the piles. So the plies are friction end-bearing piles. The load from the bottom surface above was all on the end-bearing piles and finally transferred to the hard sub-rock layer or sub-soil layer, and a dislocation appeared between the spillway bottom and the contact surface of base earth. The dislocation eventually led to contact flushing. On-the -spot inspection discovered that level cracks first appeared between the junction of the gate bottom and the dam body .Because the gate bottom was of rigid structure and the dam body was of uniform earth, flexible structure, and the uncoordinated deformation between the rigid structure and flexible structure first led to level cracks(see fig.4). Meanwhile, the connection between the gate bottom and the two wing walls was rigid. When the gate bottom was jacked by reinforced piles, uncoordinated deformation between the junction of the wing walls and the dam body made the settlement of wing walls smaller than that of the base earth .So vertical cracks appeared on the sides of the gate bottom. When influenced by outside forces, cracks develop on the contact surface .And the earthquake compounded the cracks or the dislocation between the spillway and the dam body, finally created seepage tunnel.

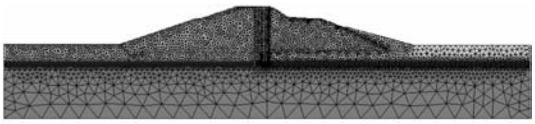
## 3 Seepage calculation and analysis

From the above analysis, the conclusion is that the breach of the One Reservoir spillway and the seepage are closely related, and we can even say that the breach of the spillway is a direct result of the seepage. So it is necessary to analyze the seepage characteristics of the dam before and after the breach.

### 3.1 Finite element calculation analysis of the seepage

Finite element calculation analysis of the One Reservoir spillway section is carried out to compare the seepage before/after the cracking of the spillway gate bottom .According to the geological survey, the permeability coefficient of the dam body earth is $9.33\times10^{-8}$cm/s~$2.00\times10^{-5}$cm/s,average value $3.54\times10^{-6}$cm/s;the permeability coefficient of the fine sand stratum is $3.50\times10^{-3}$ cm/s~$8.50\times10^{-3}$cm/s，average value $6.00\times10^{-3}$cm/s；the permeability coefficient of the gravel layer is $1.73\times10^{-3}$cm/s~$3.64\times10^{-2}$cm/s，average value $1.34\times10^{-2}$cm/s。From the project practice we can have the permeability coefficient of the spillway concrete ,$1.00\times10^{-10}$cm/s; the permeability coefficient of dam base loess $2.00\times10^{-5}$cm/s。

The specific situation before/after the dam taken into account, the water elevation is valued at 3320.27m.And the seepage calculation analyses are made under the two circumstances, before /after the breach of the dam. According to the safety evaluation inspection on the spot, there was 8cm settlement at the junction of the spillway entrance and the reservoir area, and there was also a crack, 5cm~10cm wide, 6m long. But no shoring was done. Therefore, in the finite element analysis model, vertical cracks below from the junction of the gate bottom and the dam body and above from the spillway bottom are simulated. Physical models are built as illustrated in fig.6 and fig.7.The potential energy distribution through the seepage calculation is illustrated in fig.8 and fig.9.



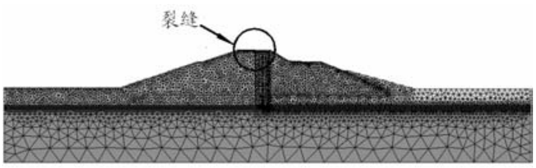
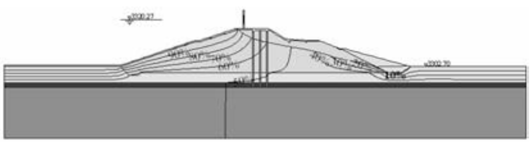



Fig.6 Finite element grid before cracking　　Fig.7 Finite element grid after cracking



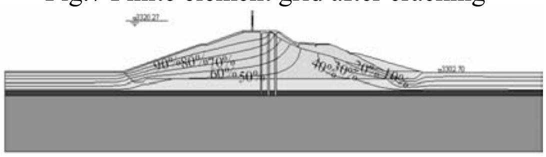


Fig.8 Seepage field distribution before cracking Fig.9 Seepage field distribution after cracking

From the results of finite element calculation we can conclude: (1) the phreatic line after the cracking was higher than before the cracking. Because with the continuous seepage of water into the dam body, the phreatic line became higher and higher. From unsaturated soil mechanics we know that the effect of unsaturated soil suction on the shear strength of dam body earth can be explained by Fredlund’s mechanical for unsaturated soil shear stress. Before the appearance of the cracks, unsaturated part of the dam body dominates, thus leading to soil suction (minus pore water pressure) and improving the stability of the dam body. But after the appearance of cracks, the soil suction decreases, threatening the stability of the dam body. (2)After the cracking, the hydraulic slope has a definite increase toward the lower reaches. If the hydraulic slope is slightly higher than the critical hydraulic slope, the dam body earth will deform .(3)When there is no crack between the spillway gate bottom and the dam body, the hydraulic slope at the foot of the dam is 1.01,more than maximum hydraulic slope 0.793 under seepage deformation circumstances, but smaller than the critical hydraulic slope of dam body earth,1.190;when the cracks appear ,the hydraulic slope is 1.21 ,far more than maximum hydraulic slope 0.793 under seepage deformation circumstances and the critical hydraulic slope. Therefore, the cracks at the junction of the dam body and the spillway are the culprit of the destructive deformation. And the dam is threatened by seepage destruction. (4)Before the appearance of the cracks, the level seepage slope is 0.197,the seepage slope of the outlet section is 0.031.By comparison with the seepage slope and the outlet section slope regulated by the Water Gate Design Codes(the level seepage slope 0.25~0.35、the outlet section slope 0.50~0.60, we can conclude that the seepage characteristics are safe before the appearance of the cracks between the gate bottom and the dam body. After the appearance of the cracks, the seepage slope is 0.772, and the outlet section slope is 0.113.By comparison with the regulation by the Water Gate Design Codes, the seepage characteristics are unsafe. In fact, because of the cracks at the junction between the gate bottom and the dam body, there is piping in the weakest link of the dam body earth. At the same time, small flushing ditches are detected below the gate bottom, and these small ditches evolve into a large one and the piping tunnel is thus enlarged rapidly and develops toward the upper reaches. Finally soil underneath the bottom is flushed out and the bottom is destroyed, as described by the Reservoir workers.

3.2 The calculation of the length of the spillway gate bottom

Because the spillway is based on the uniform dam earth, the gate base can be taken as uniform earth foundation. By the Water Gate Design Codes (SL265-2001), the length of seepage –proof in the base of water gate should satisfy the formula (1) [8].

$$L = C\Delta H \qquad (1)$$

In which: L stands for the length of seepage-proof in the base of water gate, or the sum of the level length and vertical length of the seepage-proof line in the base of water gate.(m);C maximum permeability coefficient value. From the geological survey, we know that the breached spillway -section dam body is made of sandy silt of low liquid limit. The reference value is 5.0. $\Delta H$ Water head difference between the upper and lower reaches.

The water elevation at the dam breach time is 3320.21m, and water head difference between the upper and lower reaches is 17.93m.By calculation, we can have the ideal L, 89.65m.as a matter of fact, the real length is only 43.48m.far falling short of the demands by Spillway Design Codes.

3.3 The actual seepage characteristics when the spillway breached

Because of the existence of the level cracks between the spillway gate bottom and the below dam body, and because of the existence of the vertical cracks between the two wing walls and the dam body ,water seeped into the dam body when the reservoir water was running higher above the spillway bottom elevation. On-the-spot inspection showed that on March 30th, the elevation of the reservoir water was 3319.50m, higher than the spillway bottom elevation 3319.40m.In the following days the reservoir water level was also higher than the bottom elevation, except on April 17th, the water elevation was 0.2m lower than the bottom elevation. On April 16th,the water elevation was even as high as 3320.80m.(See in fig.10).Under the continuous one-month long influence of the high water elevation ,the crack section acted on the total water head and there was contact flushing inside the dam body, forming the seepage tunnel under the reservoir water pressure. The two earth quakes at19:43 April 27th and at 0:07 April 28th enlarged the existing seepage tunnel, and the seeping water further flushed and scoured the dam body and the slope in the lower reaches. From the analysis above we conclude that the cause of the dam breach is the seepage caused by the cracks at the junction of the spillway bottom and its wing walls.

As showed by the evidence provided by the Qinghai Province Seismological Bureau ,two earthquakes broke out at the junction of Wulan County and Dulan County April 27th -28th, 2005, and the seism epicenter is only 60-70km away from the One reservoir. From the on-the-spot inspection we know that during the earthquake time house and electricity poles were shaking ,and the tableware fell from the cupboard in the nearby resident' house. By comparison with the Chinese Earthquake Scale Table, it is judged that the scale of the two earthquakes is about V~VI.

The level acceleration was only 0.31~0.63m/s$^2$ (equivalent to 0.05g), so the dam was stable in the process of the earthquakes.

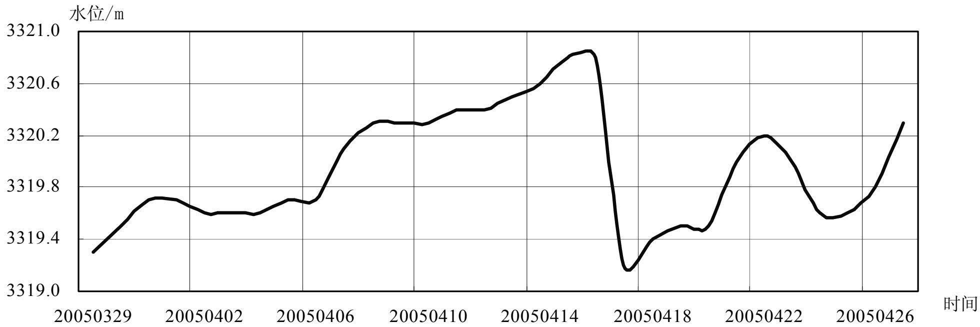
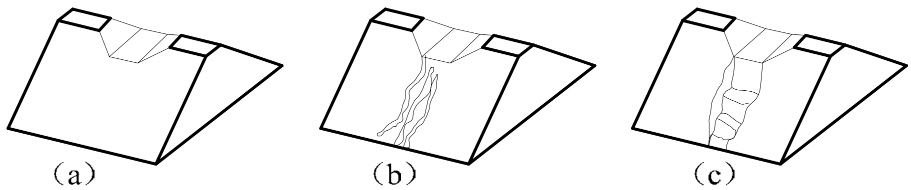



Fig.10 One-month-long water elevation curve before the dam breach

## 4 The process of the dam breach

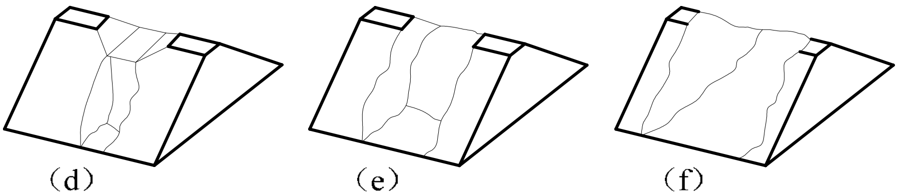
There was long-time water flushing in the cracks between the spillway gate bottom and the two wing walls, meanwhile, overflow from the top flushed the slope in the lower reaches and developed many small ditches. With the continuous flushing, these small ditches formed ditch grid and finally evolved into larger ones. There were many step-like small slope in the ditches(see fig.11c) , and as time went by ,these small step-like slope made their way toward the upper reaches and at the same time they became wider and wider, eventually they formed large sharp slopes. (See fig.11d)The bottom in the lower reaches was partly emptied by the flushing water. Under the influence of the flushing water, these sharp slopes further made their way upward till at last they reached the edge of the dam top. Then they reduced the elevation of the breach part on the top of the dam and the spilling water volume increased violently (see fig.11e), and finally the spillway was completely breached. (See fig.11f). The enlargement of the ditches and the develop -ment of the sharp slopes toward the upper reaches in the dam breach process are results of water turbulent in the flushing area in the lower reaches and its shear stress. The flushing water was continuously scouring the sharp slope, and finally caused the vertical wall side to lose stability and collapse, thus enlarging the collapsed cutting and making the sharp slopes develop upward.




(a) seeping water flushing the cracks between the spillway bottom and the two wing walls;

(b) Appearance of small flushing ditches

(c) Small ditch grid developing into larger ditch containing many step-like sharp slopes




(d) Ditch evolving into a huge and upward aggressive sharp slope

(e) Enlarging of the breached cutting

(f) Complete breach and the breached cutting reaching its final width

Fig.11 the process of the breach of the spillway of the One Reservoir

## 5 the repair of the reservoir

The repair of the reservoir consists of two parts: the repair of the breached dam and the re-building of the spillway .In order to avoid uneven subsidence and the subsequent cracks, complete slope cutting has to be carried out to make the sharp slopes of the collapsed dam body and the upper reservoir area becomes soft slopes. The foundation has to be compacted and the back fill earth has to be rolled and compacted. At the same time two pore monitoring equipment are to be installed in the breached section. Put soil work film under the full-crossed section of the former dam .At the junction of the soil wok film and the wave wall, the former wave wall has to be demolished and the dry stones have to be removed. The soil wok film should be put under the base of the new wave wall and even stretched beyond. New wave wall and dry stone pitching are to be built. As for the partial subsidence in the upper dam slope, digging should be carried to find out the cause of the subsidence and back fill should be compacted.

Because there is neither natural outlet as spillway, nor is proper geological possibility to lead the spilling water to the nearby gullies. Research is done to decide where to build the new spillway, and the topography and geological situation are both taken into account. The overflow weir is built on the axis line of the right and left dams, and the left bank spillway is beyond the dam shoulder, with a total length of 324.15m. 0+000～0+056.15 section foundation based on the Quaternary Period' s fluent and diluvia fine sand soil is to be dug and be replaced, with 2.2-3m thick gravel underlying the rebuilt section .The right bank spillway is located on the dam axis 0+516.6m, with a total length of 314.1m. 0+000～0+235.84 section foundation based on the Quaternary Period' s fluent and diluvia fine sand soil is to be replaced. Before replacing the base, anti subsidence deal has to be done. By comparison, there is no cost difference between the two design plans. If the spillway is built on the uniform earth dam, it will be a threat to the dam body. According to the geological situation, it is better to have the new spillway built on the left bank, the base of which is basically graveled.

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