Analysis of the Effect of Wenchuan Earthquake on Qiaoqi Dam

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ABSTRACT:

The Qiaoqi Dam on the Baoxing River is a rockfill dam with gravelly soil core. The dam height measures 125.5m and the overburden as the dam foundation is about 70 meters thick. The dam site was shocked intensely during 5.12 Wenchuan Earthquake at an epicentral distance of about 71 kilometers. The dam is well instrumented to monitor its working sate. Through the contrastive analysis on the pre-earthquake and post-earthquake monitor data of the deformation, stress and strain, seepage flow and seepage pressure of the dam, the impact of the Wenchuan Earthquake on Qiaoqi Dam was obtained. The result showed that the dam remained a normal working state after the great earthquake. However, certain effects were displayed on the dam's deformation, seepage and stress and strain. Especially, some parts of the grouting curtain in the left abutment were damaged by the earthquake.

KEYWORDS: Wenchuan earthquake; Rockfill dam; Deformation; Seepage; Dam safety against earthquake

1 INTRODUCTION

The Qiaoqi waterpower station, with a total reservoir capacity of 212 million cubic meters, is the project with the biggest reservoir of the cascade development on Baoxing River. Located at the junction of the east wing of Jintang arc geo-fracture and Longmen Mountain fault zone，the anti -seismicintensity for the dam design is Ⅷ degree. And the dam site was shocked intensely during 5.12 Wenchuan Earthquake at an epicentral distance of about 71 kilometers. The dam is well instrumented to monitor its working sate. Through the contrastive analysis on the pre- earthquake and post- earthquake monitor data of the deformation, stress and strain, seepage flow and seepage pressure of the dam, the impact of the Wenchuan Earthquake on Qiaoqi Dam was obtained and the dam's safety against earthquake was evaluated.

2 DESCRIPTION OF THE QIAOQI DAM

The Qiaoqi Dam with the height of 125.5 m is a rockfill dam with gravelly soil core. The length and width of the dam crest is 433 m and 10 m. The upstream slope of the dam is 1:2.0 and a sperm is arranged at the elevation of 2090 m, while the downstream slope is 1:1.8 with a 5 m width sperm at the elevation of 2085 m as shown in Figure 1. The dam toe is integrated with the downstream cofferdam. On the left abutment at the dam toe, waste materials are backfilled to the elevation of 2035 m, while a notch, which is linked to the river channel on the right abutment at the dam toe, is set to discharge the dam seepage flow. The maximum transverse and longitudinal cross section of the dam are shown in Figure 1 and Figure 2 respectively.

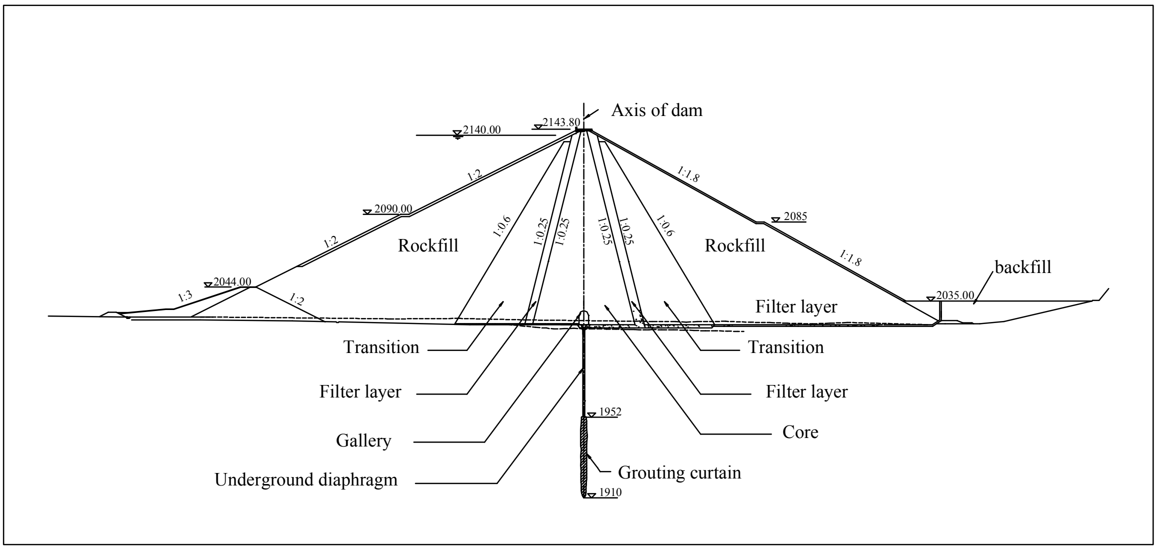


Figure 1 Maximum transverse cross section of the Yele Dam

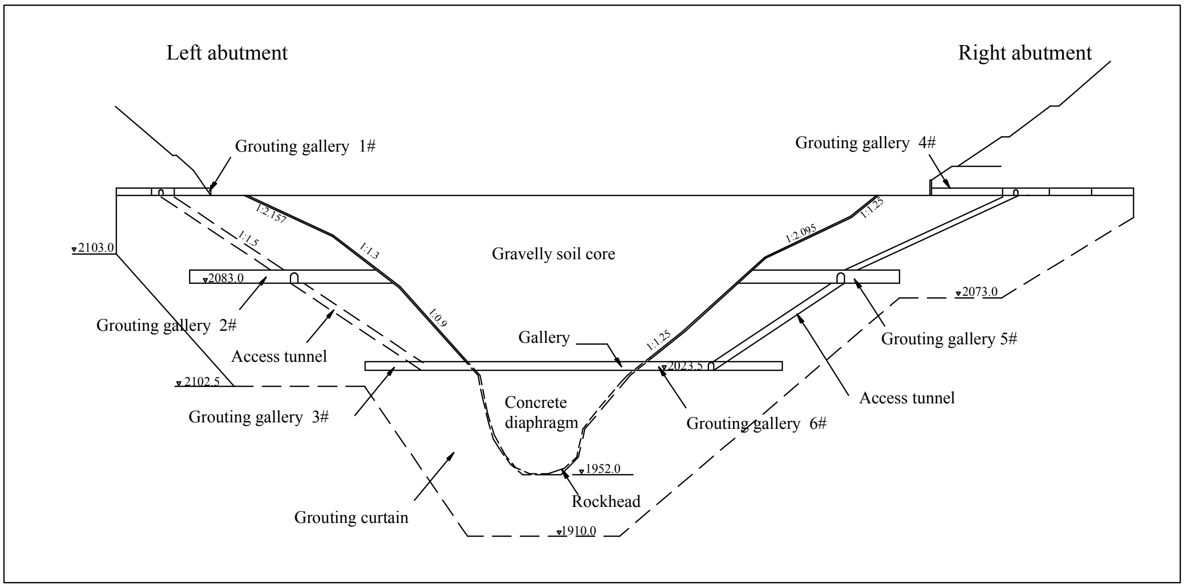


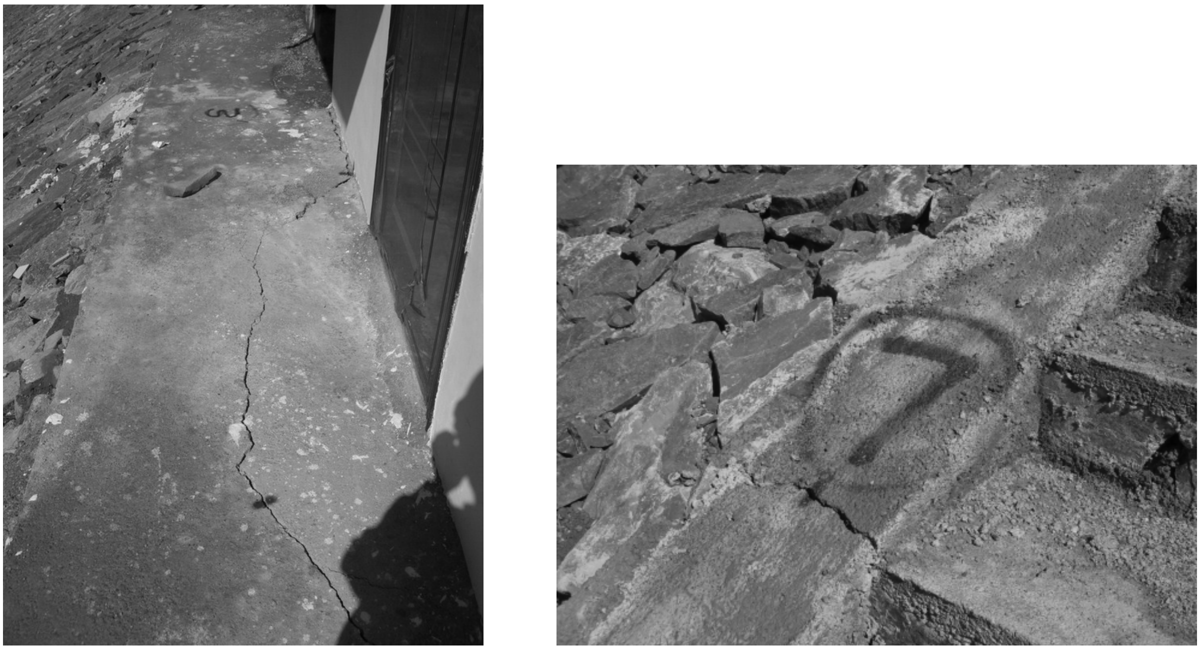
Figure 2 Maximum longitudinal cross section of the Yele Dam

The overburden on the river bed, which is about 70 m thick, consists of fluvial gravel stratum with boulder contained, block and gravely stratum, and gravel soil stratum. Since the moderate or strong permeability of the natural foundation material, concrete diaphragm and grouting curtain are used to control the seepage of dam foundation. The concrete diaphragm is 1.2 m thick and 70.5 m deep. Stiff joint is adopted at the connection of the diaphragm and its top gallery, where no structural joints exist. Highly plastic clay is arranged above the top and in the upstream and downstream of the gallery as well. A horizontal filter, 1.0 m thick, is set between the core on the downstream side of the diaphragm, transition region, rockfill zone and the riverbed. Under the concrete diaphragm, grouting curtain is carried out by two grouting holes. And three horizontal grouting tunnels are set in the left and right abutments as indicated in Figure 2. Finally, the grouting curtains within abutments are carried out through these tunnels and the bank slopes under the core.

3 OBSERVED DAMAGE

The following was concluded from the inspecting around the dam half an hour after the great Wenchuan earthquake on May 12, 2008:

(1) Several cracks appeared on the downstream surface of the dam. The typical cracks resulting from the Wenchuan Earthquake are along the dam axis as follows: Beside the observation house on the dam crest in the left abutment, a 5.79 m long and 10 mm wide crack was shown in Figure 3 (a); another 2.23 m long and 7 mm wide crack was on the downstream steps in the biggest cross section, which is located in the position of 3/4 dam height shown in Figure 3 (b).



(a) dam crest (b) surface of the dam downstream slope

Figure 3 Cracks induced by Wenchuan Earthquake

(2) A 1 mm wide crack, which was along the structural joint, appeared on the bottom plate of the connection between the inspection gallery and 3# grouting tunnel. The cemented concrete was unstuck in the upstream of the structural joint bottom.

(3) The seepage discharge of the access tunnel on right abutment seemed a bit more and the water was turbid.

However, it turns to be some calcium deposits on the bottom plate shook into the drain and resulted in the turbidity. The water in the side drains of the gallery was clear.

(4) No abnormal phenomenon was found on the upstream surface of the dam. No caving, bulking or collapse appeared. There was no effervescency or swirl on the water surface in front the dam. On the downstream surface, no caving, bulking or collapse appeared, no soakaway, piping or soil flowing.

(5) The drainage system in the foundation was working in order. No rupture or water seepage existed in the joint of the dam and abutments. Rocks fell and landslide on the abutments are absent. In addition, no piping, flowing soil or uplift occurred near the dam toe.

4 SEISMIC RESIDUAL DEFORMATION

4.1 Surface Residual Deformation

Fifteen observation points were arranged to obtain the deformations of the dam surface on 3/4, 1/2 and 1/3dam height respectively in several cross sections. It was proved that the settlement of the dam in riverbed was greater than that of the dam in abutments. The transverse deformation of the dam's upper part was larger than that of the lower part. The upstream slope deformed towards to the upstream while the downstream slope moved to the downstream. In the longitudinal direction, the dam body below 1/3 dam height shifted to the left and right abutments according to the biggest cross section, while the other 2/3 part of the dam had a deformation toward the biggest section.

Table 1 The deformation of dam surface in the biggest cross-section (mm)

Position		Dam crest	3/4 dam height	1/2 dam height	1/3 dam height
Distance from dam axis (m)		0	65.00	109.4	158.0
Transverse	Pre-earthquake	-	360.35	391.0	275.7
	Post- earthquake	-	333.4	377.1	273.1
	Residual deformation	-5.0	-26.95	-13.9	-2.6
Longitudinal	Pre-earthquake	-	5.6	-9.7	9.4
	Post- earthquake	-	19.5	-0.2	24.5
	Residual deformation	8.0	13.9	9.5	15.1
Vertical	Pre-earthquake	-	473.33	625.7	165.4
	Post- earthquake	-	538.22	651.4	175.3
	Residual deformation	153.0	64.89	25.7	9.9

Through the post-seismic observation on the parapet wall and downstream surface in several cross sections, the maximal transverse seismic residual deformation of the dam surface was 26.95 mm (the biggest cross section, 3/4 dam height), while the longitudinal maximum was 30.4 mm (3/4 dam cross section, 3/4 dam height). In the vertical direction, the maximal seismic residual deformation was 158 mm on the parapet wall in 3/4 dam cross section. The deformations of dam surface in the biggest cross section are shown in Table 1. From the deformation illustrated in Figure 4, seismic residual deformation increased from the dam toe to the dam crest. And the maximal seismic settlement was 153 mm on the parapet wall in the biggest cross section. It should be pointed out that the deformation of the parapet wall was obtained from the temporary observation station, because the construction of the dam was completed not long before.

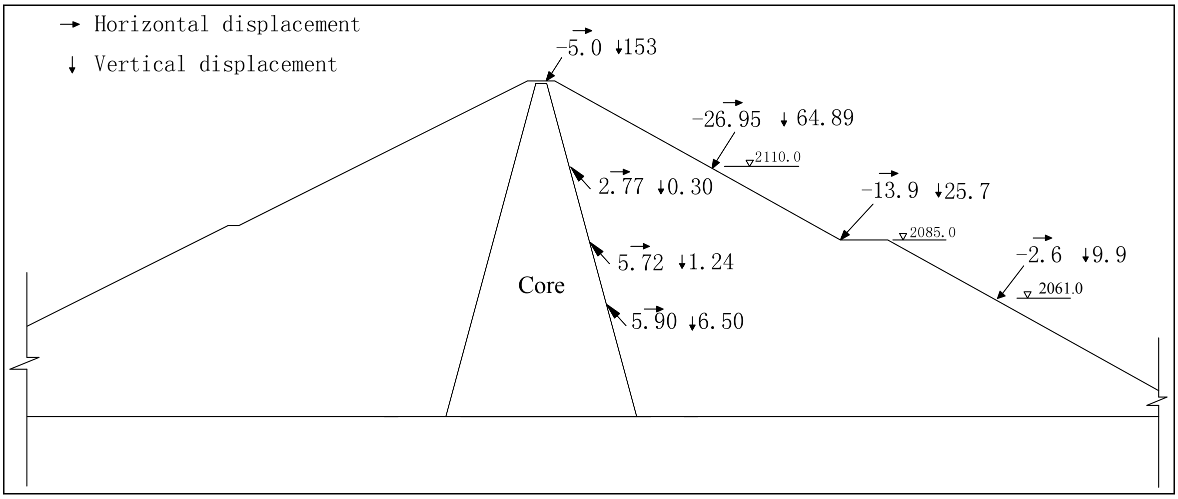


Figure 4 Seismic residual deformations of dam surface and core (mm)

4.2 Deformation of Core

Although some adiographs in the biggest cross section can monitor the transverse deformation of the core, they were all defective at present. The deformation of the core can only be acquired by the observation points on the core's downstream surface of the tension wire alignment. The displacement and settlement meters were arranged together. In the biggest cross section of the dam, they were on the 1/3, 1/2 and 3/4 dam height shown in Figure 4. The pre-seismic and post-seismic deformations of the core are given in Table 2 and the seismic residual deformations are displayed in Figure 4 as well. The largest measured residual deformation was 5.90 mm in transverse direction and 6.50 mm in vertical direction. They both appeared in the core with the 1/3 dam height. Moreover, shown in Figure 4, the seismic residual deformation of the core was larger when the position was closer to the bottom of the dam.

Table 2 The deformation of core in the biggest cross section (mm)

Position	Distance from dam axis (m)	Transverse		Vertical	
		Pre- earthquake	Post- earthquake	Pre- earthquake	Post- earthquake
3/4 dam height	10.00	414.84	417.61	545.22	545.52
1/2 dam height	16.03	383.67	389.39	747.83	749.07
1/3 dam height	22.05	203.87	209.77	1272.10	1278.60

4.3 Deformation Of Underground Diaphragm

There were eight observation points on the underground diaphragm in the dam's biggest cross section. Table 3 lists the transverse displacements obtained by these points. The positive value means the displacement towards to the downstream while the negative one means the upstream deformation. Figure 5 demonstrates the distribution of the deformation along the elevation. From Figure 5, the diaphragm deformed towards to the downstream on the whole and the displacement of the upper part was larger than that of the lower part. The two curves were almost coincident due to the small change of the diaphragm's displacements before and after the Wenchuan Earthquake. The maximum of the transverse seismic deformation was only 2.2 mm, which illustrated the tiny effect of the earthquake on the underground diaphragm.

Table 3 The transverse deformation of underground diaphragm

No.	IN1	IN2	IN3	IN4	IN5	IN6	IN7	IN8
Ele.（m）	2018.00	2013.00	2006.00	1998.00	1986.00	1979.00	1957.00	1952.00
Pre- earthquake	46.2	54.4	86.0	56.8	-20.2	34.5	-17.3	-6.3
Post- earthquake	45.5	55.0	86.0	59.0	-19.7	35.2	-17.0	-6.3

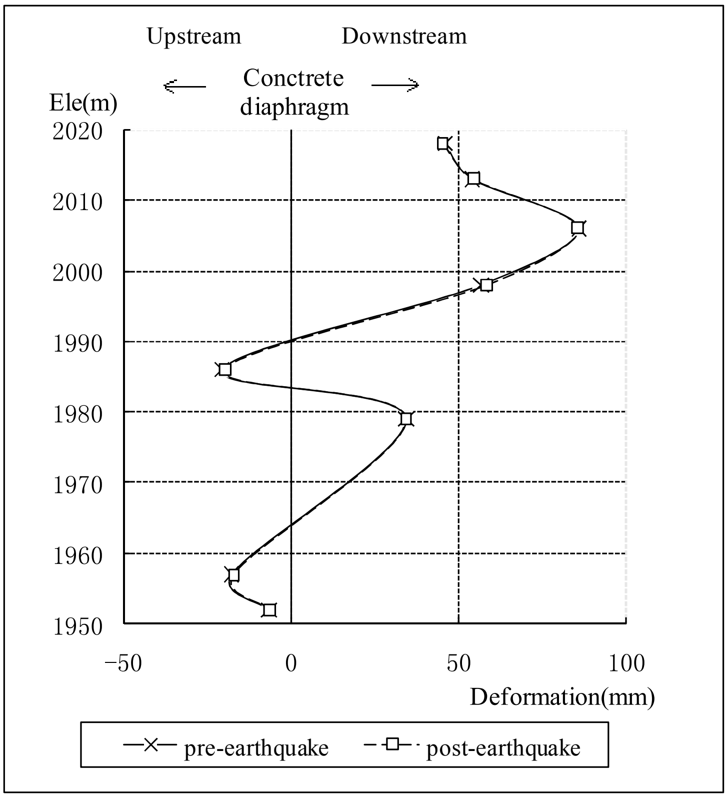


Figure 5 Seismic residual deformations of the underground diaphragm

4.4 Deformation Of Gallery

In the inspecting gallery and access tunnels in left and right abutments, nineteen settlement observation points were established. Because stiff joint was adopted at the connection of the underground diaphragm and its top gallery, the record values of the inspecting gallery could display the relative settlements of the underground diaphragm and the abutments. In the construction period, the settlements increased slowly and the middle of the gallery, which was above the concrete diaphragm, settled more than the parts in the abutments. The Figure 6 shows the pre-seismic and post-seismic settlements of the inspecting gallery. It was obvious that the gallery had been caused a seismic residual deformation and the maximal settlement, which was 13.20 mm, occurred in the middle of the gallery. The settlements and seismic residual deformation are listed in Table 4. These values showed that the earthquake had a certain effect on settlements of the inspecting gallery, but the effect was small.

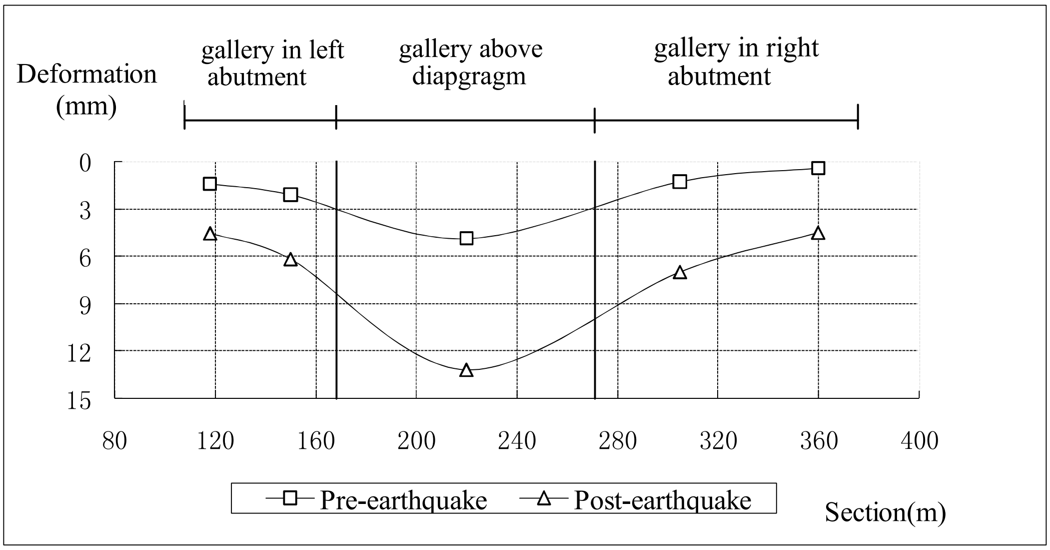


Figure 6 Settlement of inspecting gallery

Table 4 The settlements of inspecting gallery (mm）

Position	Gallery in right abutment		Gallery above diaphragm	Gallery in left abutment	
No.	S1	S2	S3	S4	S5
Pre-earthquake	0.43	1.29	4.88	2.11	1.43
Post-earthquake	4.52	7.01	13.20	6.19	4.56
Residual deformation	4.09	5.72	8.32	4.08	3.13

4.5 Deformations Between Dam And Abutment

The relative displacements of the core and abutments were monitored by the measuring points in the connection position. At present the still working soil displacement meters were on the 3/4 dam height in the left and right abutments respectively. From the record values, the longitudinal deformation of the core in the left abutment increased when the dam height rose. The tensile area of the core was within 30 m away from the left abutment in longitudinal direction and the maximal tensile displacement was107.1 mm. It occurred at the junction of the core and the plastic clay. After the earthquake, the maximal relative displacement grew and varied for 2.9 mm. The deformation of the core relative to the right abutment was like that of the core to the left abutment. But the farthest point of the core's tensile area was 24 m away from the right abutment and the tensile displacement changed for 0.4 mm due to the earthquake. Besides, the core settled relative to the abutment slopes. The relative displacements along the slope increased a little, the maximum of which was 0.032 mm in the left abutment and 0.01 mm in the right abutment.

The maximal relative displacements of the core and abutments in the longitudinal direction and along the abutment slopes are given in Table 5. The pre-seismic and post-seismic data shows the tiny seismic residual deformation. It could be concluded that the joints between the core and abutments still had good contacts after the earthquake.

Table 5 The maximal relative displacement of the core and abutments (mm）

		Position	Pre- earthquake	Post- earthquake
Transverse	Left abutment	3/4 dam height	46.3	49.2
	Right abutment	3/4 dam height	33.7	34.1
Along slope	Left abutment	2104.00	1.116	1.148
	Right abutment	2045.00	7.99	8.00

5 THE EFFECT ON SEEPAGE

5.1 Seepage Pressure Of Dam

Based on the dam height and characters of the dam’s seepage field, seepage pressure was inspected in the core, filter, transition and rockfill zones. Figure 7 shows the seepage pressure distribution of the dam downstream in the biggest cross section. Because of the small change of the seepage pressure before and after the Wenchuan Earthquake, the two curves were almost coincident. And the pressure fell down rapidly in the core. Table 6 lists the seepage pressure values in the biggest cross section. According to the table, only the record values of osmometers within the core changed little during the earthquake. Contrastively, there was still no seepage pressure in the filter, transition and rockfill foundation, which indicated the drainage system in downstream foundation performed very well. Overall, in the biggest cross section the maximal change of the seepage pressure was 0.8 m in the core. The little change demonstrated the little effect on the dam’s seepage pressure of the earthquake.

Table 6 The seepage pressure in the dam (m)

position	Core					Filter	Transition	Rockfill		
No.	P4	P6	P7	P8	P9	P12	P14	P18	P19	P20
Distance From dam axis (m)	3.0	3.0	3.0	3.0	10.0	27.0	50.0	120.0	170.0	225.0
Arranged elevation (m)	2126.5	2086.0	2070.0	2050.0	2031.0	2050.0	2031.0	2018.0	2018.0	2018.0
Pre-earthquake	2127.4	2108.7	2098.5	2110.9	2070.9	2050.0	2031.0	2018.0	2018.0	2018.0
Post-earthquake	2127.3	2108.6	2097.7	2111.6	2071.7	2050.0	2031.0	2018.0	2018.0	2018.0

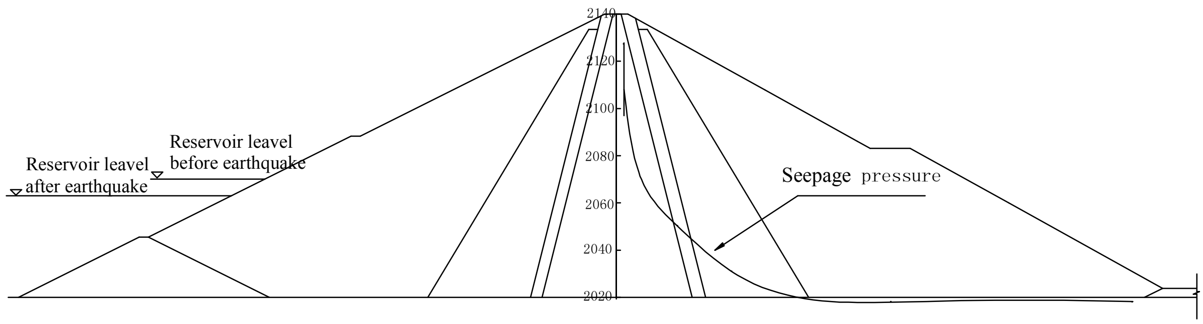


Figure 7 Seepage water pressure distribution of max transverse cross section (m)

5.2 Seepage Pressure Of Abutments And Foundation

In the left abutment, no water existed or the piezometric levels almost kept no change in the access tunnel. The grouting curtain (elevation 2036m～2077m) was not affected by the earthquake. The water levels of two piezometer tubes in $2^{\#}$ grouting gallery were stable before and after the earthquake. But the recent water levels of another piezometer tube UP5 were all higher than the reservoir level, which might be influenced by the pressure water enclosed in the rock fissures. In detail, the piezometric level of UP5 on May 15 and 18 was 2 m and 4 m higher than that on May 9 and 10 respectively. Because of no rain in the dam site from May 14 to 18, the water level of the abutments would not rise due to the rain or the reservoir level. Therefore, the underground water within the left rock abutment may be affected by the earthquake to some extent. The piezometric level in $3^{\#}$ grouting gallery varied with the reservoir level and ascended after the earthquake. Contrast to pre-seismic record under the same reservoir level, the piezometric level behind impervious curtain in the left abutment ascended 1.8 m. It can be concluded that the earthquake had certain effect on the grouting curtain (elevation 2021m～2024m).

In the right abutment, no water existed or the piezometric levels almost kept no change in the access tunnel. The grouting curtain (elevation 2034m～2072m) was not affected by the earthquake. The piezometric levels in $5^{\#}$ grouting gallery varied little, which indicated that the earthquake also had little effect on the grouting curtain (elevation 2081m～2083m). In $6^{\#}$ grouting gallery, the piezometric level increased with the rising of the reservoir level recently. But on May 18, the water level decreased for 2.5 m contrast to pre-seismic record under the same reservoir level. Thus no disadvantageous effect was made on the grouting curtain (elevation 2020m～2024m) by the Wenchuan Earthquake.

The seepage pressure at the upstream of the concrete diaphragm varied with the reservoir level and the rate of seepage pressure changing decreased a little. It illustrated that little effects were made on the diaphragm. Piezometer tubes in the inspecting gallery were designed to monitor the seepage of the contact surface between different materials and the seepage in the foundation. The water levels of the piezometer tube UP13 and UP15, which were behind the diaphragm in the horizontal gallery, only had a little change. And the piezometric level of UP14 rose with the rising of the reservoir level before the earthquake, but reduced by 1m on May 18, contrast to the level under the same reservoir level before.

In addition, thirteen observation wells were along the streamline in the abutments and the contact zones of the dam and abutments. The underground water table could be obtained through the nilometers in them. In fact, no water was found in the wells before and after the Wenchuan Earthquake.

5.3 Seepage Discharge

In the drains of the gallery, measuring wells were arranged to inspect the seepage discharge of the dam. As the rising of the reservoir level, the seepage discharge in the gallery increased. On May 19, the measuring discharge was 4.522 L/s while it was 2.659 L/s only under the same reservoir level before the earthquake. Get rid of the reason of the reservoir level, the seepage discharge had an extra increment of 1.863 L/s. This was the evidence that showed the anti- seepage system was affected by the earthquake.

6 THE EFFECT ON STRESS AND STRAIN

In order to inspect the stress and strain of the concrete diaphragm, paired strain gauges were laid out in the biggest section of the dam. The data was given in Table 7. The record values before the earthquake showed that the compressive stress of the diaphragm increased as the height of the reservoir level rises and the dam construction. The stress fluctuated for a maximum of -0.339MPa, which showed the earthquake had little effect on the diaphragm's stress or strain.

Table 7 The stress and strain of the concrete diaphragm

No.	Position	Strain (με)		Stress (MPa)	
		Pre-earthquake	Post- earthquake	Pre- earthquake	Post- earthquake
S1	2016.00	-557.94	-568.90	-16.738	-17.067
S2	2016.00	-605.57	-611.26	-18.167	-18.338
S4	2006.00	-193.45	-204.74	-5.803	-6.142
S5	1986.00	-435.12	-437.76	-13.054	-13.133

Three observation sections were arranged in the core to monitor the inner stress and the contact stress of the core and abutments. The positions of these sections were as same as those of the deformation monitoring section. The pre-seismic data showed that the stress of the core in construction period rose gradually with the rising of the dam construction height. The maximal soil pressure recently was -1.019 MPa (the biggest section, elevation 2032.5 m). And the little change of the pressure gauges' record values illustrated that the effect of the earthquake on the core was small.

The reinforcements in three observation sections of the gallery were almost compressed, and the compressive stress increased with the rising of the dam construction height. But the stress was within bounds of the reinforcements. The record values varied for a maximum of 2.67MPa only, which indicated the little effect on the reinforcements by the earthquake.

7 CONCLUSIONS

(1) No abnormal phenomenon was found due to the earthquake. No caving or bulking appeared on the dam surface and the drainage system in the foundation was working in order. No water seepage, piping, flowing soil or uplift occurred near the dam toe. But some small cracks were found on the downstream surface of the dam and the bottom plate of the inspection gallery as well.

(2) The dam had some seismic residual deformations. The largest residual deformation measured on the surface was 26.95 mm in transverse direction, while with 30.4 mm longitudinal deformation and vertical deformation of 158 mm. The largest residual deformation of the core was 5.90 mm transversely and 6.50 mm vertically. And the gallery in the dam foundation, together with the transport tunnels on both abutments, had settled maximum 8.32 mm after the earthquake. The deformation of the underground diaphragm caused by the earthquake was very small. Finally, the joints between the core and abutments still had good contacts after the earthquake.

(3) The record values of osmometers within the dam changed little during the earthquake, which indicated the

little effect on the dam's seepage pressure of the earthquake. The dam's gravelly soil core was working in order. The rate of seepage pressure changing of underground diaphragm decreased a little. It illustrated that little effects were made on the diaphragm. However the earthquake had impaired the curtain in left abutment to some extent. Contrast to pre-seismic record under the same reservoir level, the piezometric level behind impervious curtain in the left abutment ascended 1.8 m. Moreover, the post-seismic seepage discharge in the right abutment had an extra volume in addition to increment induced by the rising of reservoir level. This is the evidence that showed the anti-seepage system was affected by the earthquake.

(4)The effect of the earthquake on dam body, underground diaphragm and the reinforcement within the gallery was small, since the record values of pressure gauges varied little in the dam body, underground diaphragm and the gallery.

(5) Based on the analysis on the data of the deformation, seepage, stress and strain, and combined with the inspecting result, the maximal seismic residual settlement of the Qiaoqi Dam was not great with the magnitude of 158 mm; the seismic deformation of underground diaphragm was rather small and little effect was made on the seepage prevention; the joints between the core and abutments are still in good contacts after the earthquake. Therefore, the Qiaoqi Dam remained a normal working state after the 5.12 Wenchuan Earthquake. But some parts of the grouting curtain in the left abutment (elevation of 2021m～2024m) might be damaged by the earthquake.

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