SEISMIC RESPONSE FEATURES OF YELE DAM IN WENCHUAN EARTHQUAKE

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ABSTRACT:

YeLe Dam with the height of 124.5m is a rockfill dam with asphalt concrete core. The dam is located in the earthquake-prone area and the geological condition is quite complicated. The dam site was shocked intensely during 5.12 Wenchuan Earthquake at an epicentral distance of about 258 kilometers. The seismographic array on the dam, which consists of nine strong motion seismographs, obtained comparatively complete records of the Wenchuan Earthquake. The duration of the record is as long as 200s, which is very rare in dam's earthquake record data. Base on these seismic records, the time history and spectral analysis is carried out to explore the YeLe Dam's dynamic response features. The seismic duration of each position is found different, as well as the peak time. The acceleration extremums occur both at the crest and toe of the dam and the response shows dissymmetric between the left and right abutment. Moreover, the dam's acceleration spectrums have the features of narrow band and low dominant frequency.

KEYWORDS: Wenchuan Earthquake, Rockfill dam with asphalt concrete core, Seismic record, Time history analysis, Spectral analysis, Dam safety against earthquake

1 INTRODUCTION

The YeLe Dam on the Nanya River is a rockfill dam with asphalt concrete core. The dam height measures 124.5m, which is the highest in China and the third one worldwide among this dam type, next to the Kopru dam with the height of 139 m in Turkey and the Storglomvatn dam with the height of 128 m in Norway. The dam site was shocked intensely during 5.12 Wenchuan Earthquake at a distance of about 258 kilometers from the epicenter (North latitude 31°00′, East Longitude 103°24′). The seismographic array on the dam obtained comparatively complete records of the Wenchuan Earthquake. These observation records offer a valuable and unique source for analyzing and learning the dynamic behavior and earthquake resistance of this kind of dams.

The YeLe waterpower station, with a total reservoir capacity of 298 million cubic meters, is the first power station with the biggest reservoir of the cascade development on Nanya River. The designing anti-seismic intensity of YeLe Dam is Ⅸ degree while the designing earthquake acceleration is as large as 0.45g. The

geologic structure of YeLe dam foundation is quite complicated and the transnormal geological phenomenon is prominent. The dam sits in the borderland of YeLe fault basin. On the left abutment, the shallowly embedding bedrock is steep dipping towards the riverbed. The overburden layers in the river bed and in the right abutment, which is more than 420 m thick, consist of gravel stratum, silt loam and gravelly soil of Pleistocene series in quaternary system. The illuvial horizon underwent different degrees of calcareous cementation and over consolidation in different geologic periods, which leads to the severe dissymmetric ground condition under the dam. Thus there are great difficulties in deformation compatibility and the seepage system of the dam foundation.

From December 2005 when the first use of three strong-motion instruments to December 2007, the construction of the seismographic array was completed in succession. At present, nine strong motion seismographs are placed on the dam. Eleven earthquakes had been recorded before May 12, 2008 during the past two years. The seismic response features of the dam have been acquired preliminarily. During the Wenchuan Earthquakes, eight earthquakes motions have been recorded by the dam monitoring array with highly data integrity and reliability, including the main earthquake of magnitude 8.0 as well as six aftershocks of magnitude greater than 5.0. According to these seismic records, the time history and spectral analysis is adopted to explore the YeLe Dam's dynamic response features. At the same time, through the contrastive analysis on the pre-seismic and post-seismic monitor data of the deformation, stress and strain, seepage flow and seepage pressure of the dam, the impact of the Wenchuan earthquake on YeLe Dam is obtained and the dam's safety against earthquake is evaluated. The results can provide a reference for the seismic design and research of the high rockfill dam with asphalt concrete core.

2 THE YELE DAM AND ITS SEISMOGRAPHIC ARRAY

2.1 Description of the Yele Dam

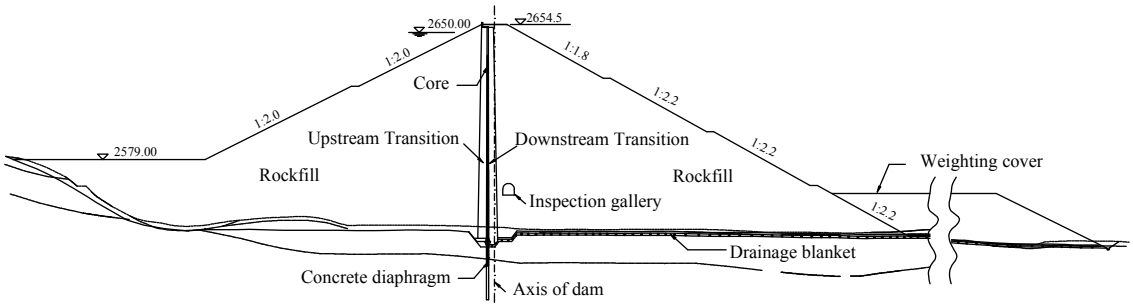


Figure 1 Maximum transverse cross section of the Yele Dam

The maximum transverse cross section of the dam is shown in Figure 1. The main dam consists of asphalt concrete core, upstream and downstream transition zones and rockfill shoulders. The upstream slope of the dam is 1:2.0. While the downstream slope is 1:1.8, 1:2.2, 1:2.2 and 1:2.2 at different portions, where three 4 m wide sperms are arranged as shown in Figure 1. The auxiliary dam on right abutment is a rockfill dam with a reinforcement concrete core. The dam height is 15 m. Because of the high artesian head of the aquiclude in dam foundation, drain holes and 215 m long weighting cover are arranged in the dam downstream. Towards the

severe dissymmetric ground condition, concrete diaphragm and grouting curtain are adopted to control the seepage of dam foundation.

2.2 Strong-motion Instrumentation

The instruments used on YeLe dam are products of Engineering Mechanics Institute at Harbin under China Earthquake Administration. Thereinto, six of them are type GDQJ-Ⅰ and the other three are type GDQJ-Ⅱ. Once a strong earthquake happens, the instrument will be triggered and start to record it automatically. The intensity will be calculated as well. The motion record is divided into three directions including EW, SN and UP. The motion towards east is record as positive value in EW direction while towards north as positive value in SN direction. And the up motion is record as positive value in UP direction.

According to the arrange principle (G.R.Darbre, 1995), the nine seismographs are fixed along the crest and the biggest transverse section of dam. Figure 2 shows the planar disposal of these instruments. Figure 3 shows the disposal of strong motion seismographs on the biggest section. Along the main dam crest, 4# seismograph is located at the centre while 1# and 10# are installed at the left and right abutment respectively. 5#, 6# and 7# seismographs sits along the dam biggest section down the downstream slope, and at approximately 3/4, 1/2 and 1/4 dam height. These six instruments are designed to record the seismic response of the main dam. The 11# seismograph at the crest as well will monitor the response of the auxiliary dam and 12# seismograph in grouting tunnel of the left abutment is wished to record the seismic response of the bedrock. What's more, because of the thin asphalt concrete core, an instrument of 13# is arranged in the monitoring gallery of the biggest transverse section so as to reveal the seismic response near the core. In addition, the horizontal accelerometers are oriented due North and East, which corresponds to the longitudinal and transverse direction respectively. And UP signifies the vertical direction.

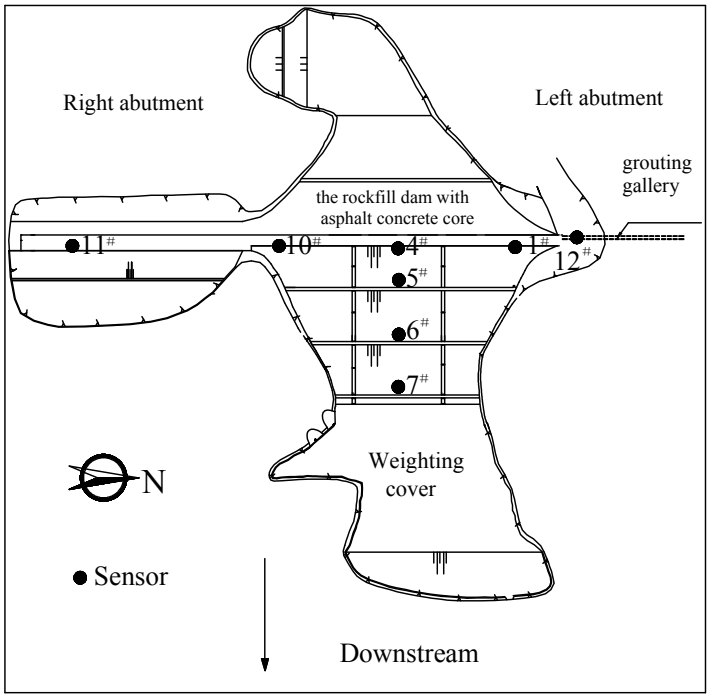


Figure 2 The planar disposal of strong motion instruments of the YeLe dam

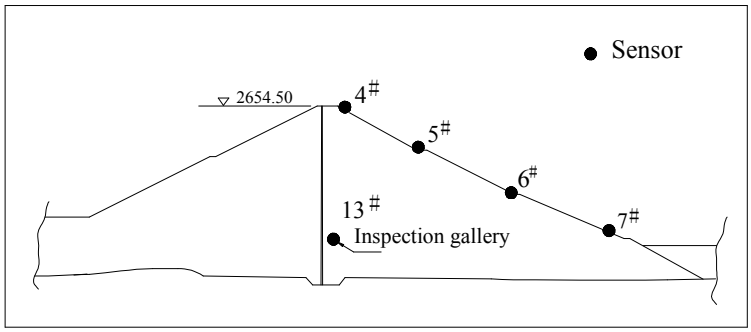


Figure 3 The disposal of strong motion instruments on the biggest section of the YeLe dam

3 SEISMIC RECORDS ANALYSIS

3.1 Seismic Records

According to Earthquake Catalogue published by China Earthquake Date Center, the essentials of each earthquake recorded by the seismographic array of Yele Dam are listed in Table 1. The first record is the main shock of 5.12 Wenchuan Earthquake. The largest aftershock occurs on May 25 with the magnitude of 6.4.

Table 1 Seismic parameters of the records in 5.12 Wenchuan Earthquake

No.	Date	Time	Magnitude Ms	Position		Epicenter distance (km)	Epicenter Depth (km)
				North latitude	East Longitude		
1 Main shock	2008-5-12	14:28:04	8.0	31°00′	103°24′	258	14
2	2008-5-12	14:43:15	6.0	31°00′	103°30	262	33
3	2008-5-12	15:34:47	5.0	31°00′	103°30	262	10
4	2008-5-12	19:10:58	6.0	31°24	103°36	306	33
5	2008-5-12	21:40:54	5.1	31°00′	103°30	262	33
6	2008-5-13	15:07:11	6.1	31°54	103°24	351	33
7	2008-5-25	16:21:02	6.4	32°36	105°24	454	33
8	2008-5-29	12:48:01	4.6	32°36	105°30	455	33

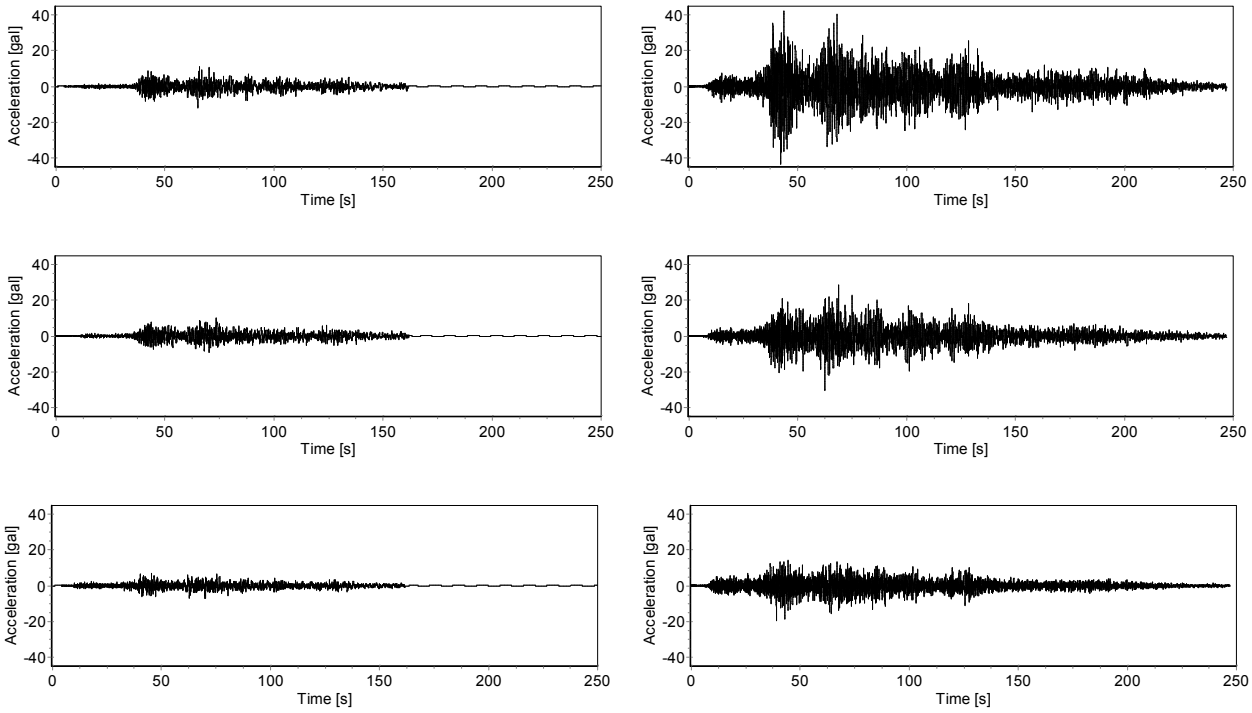
3.2 The Time history Analysis

3.2.1 Seismic durations

As shown in Figure 4, the accelerograms at 12# and 4# station is very complete and clear. The dam amplifies the earthquake wave obviously and the seismic duration is quite long. The accelerograms obtained by 5# seismograph on Dec.16, 2006, Oct.23, 2007 and May.12, 2008 are given contrastively in Figure 5. The duration of earthquake is defined as the time difference between the first and the last time when $|A(t)|>k\,|A_{max}|$ with A_{max} meaning the peak value of the acceleration (Chen Houqun, 2000). As the definition and the k is 0.2, the seismic durations of past accelerograms on Dec.16, 2006, Oct.23, 2007 are all within 20 s, but the duration of the

accelerograms in Wenchuan Earthquake is up to 223 s.

In order to analyze the seismic duration in detail, the *k* is adopted 0.05, 0.1, and 0.2 to calculate the duration. From the result in Table 2, we can see that no matter what value of *k* is, the seismic duration of the dam crest is always longer than other positions. The durations of the positions on dam surface increase as the height rising. Moreover, the seismic duration of the dam crest is longer than that of the dam toe but nearly the same as the dam bottom center. On the other hand, the seismic duration of the dam body is longer than that of bed rocks.



（a）12# station　　（b）4# station

Figure 4 Time history of transverse, longitudinal and vertical accelerations during 5.12 Wenchuan Earthquake

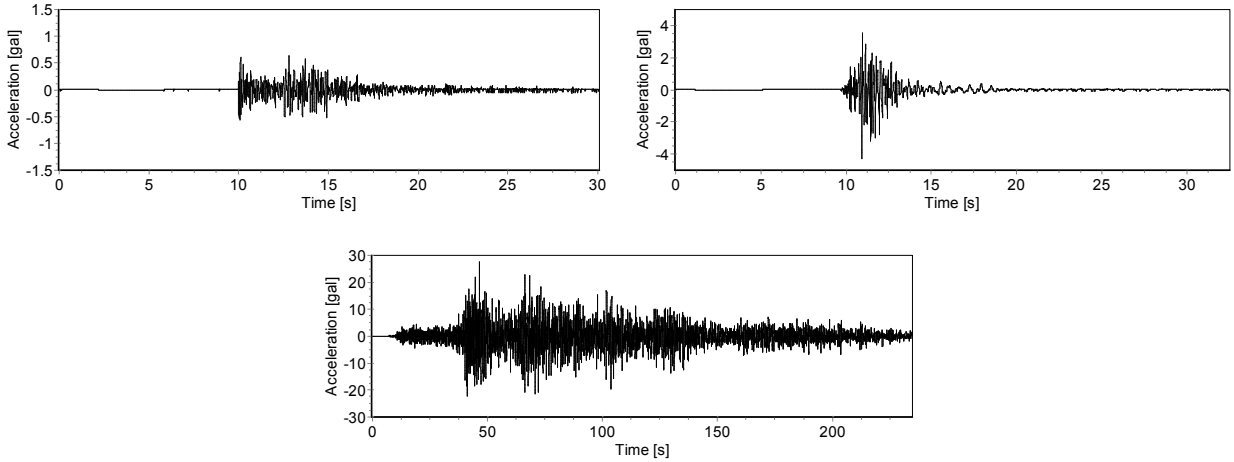


Figure 5 Time history of transverse acceleration at 5# station during the three earthquakes

Table 2 The seismic durations of each position on the Yele Dam (s)

Station	$\|A(t)\|>5\%\|A_{max}\|$	$\|A(t)\|>10\%\|A_{max}\|$	$\|A(t)\|>20\%\|A_{max}\|$
4# (crest)	231.6	216.0	194.9
5# (berm)	223.9	212.6	167.1
7# (berm)	218.1	204.5	155.9
12# (Grouting Gallery)	148.5	146.6	122.5
13# (Inspecting Gallery)	218.7	212.3	186.2

3.2.2 Acceleration peak values and times

From Figure 4, it is apparent that there are usually two peak values during the earthquake. They are called main peak and secondary peak by their arriving time. Table 3 lists the values and times of each position's main peak and secondary peak. For main peak, the peak times of dam surface's accelerations in the spatial three directions are not coincident, but basically the times of dam bottom's accelerations are the same. Peak coming time of acceleration varies among bed rocks, dam body and dam bottom. The peak values of dam crest appear earlier than those of other position on dam surface. For secondary peak, the peak times of dam's accelerations in the spatial three directions are also not coincident and there are differences in the acceleration's peak time of bed rocks, dam body and dam bottom as well. The transverse peak of dam crest appears later than those of other position on dam surface, while the peaks in the other two directions appear earlier.

Table 3 Acceleration peak values and times of each position on the Yele Dam

Station	Subentry	Main peak		Secondary peak	
		Value (cm/s^2)	Time (s)	Value (cm/s^2)	Time (s)
4# (crest)	transverse	-44.179	37.14	40.780	63.02
	longitudinal	20.371	37.73	-30.468	57.38
	vertical	-19.544	34.01	-15.505	59.42
5# (berm)	transverse	27.449	41.41	22.806	61.24
	longitudinal	-20.799	39.26	22.843	62.31
	vertical	-27.295	36.68	-16.201	62.07
7# (crest)	transverse	-34.647	37.90	27.614	62.56
	longitudinal	-23.795	33.32	24.988	58.59
	vertical	21.240	36.90	17.531	62.62
12# (Grouting Gallery)	transverse	8.616	37.20	-11.933	59.87
	longitudinal	8.160	38.70	10.267	68.40
	vertical	6.916	40.39	-7.155	64.99
13# (Inspecting Gallery)	transverse	-11.732	40.09	14.094	62.27
	longitudinal	14.809	40.00	11.151	64.78
	vertical	-8.350	40.03	9.049	64.99

3.2.3 *Peak velocity and displacement*

After the integration of the accelerograms, Table 4 shows the peak values of each position's acceleration, velocity and displacement during the earthquake on Jan. 7, 2007 and May 12, 2008. The symbol "–" means that there is no record on that position. As indicated in the table, the dam's responses of velocity and displacement calculated from the acceleration records of Wenchuan Earthquake are obviously larger. The values of 5# station are taken for example. The peak value of transverse acceleration in Wenchuan Earthquake is small than two times that of the earthquake on Jan. 7, 2007. But the peak value of velocity becomes five times and the peak displacement becomes almost a hundred times. And for 4# station, the peak values of acceleration in Wenchuan Earthquake are nearly equal to those of the earthquake on Jan. 7, 2007. But the peak value of velocity becomes four times and the peak displacement becomes almost forty times.

Table 4 Peak values of velocity and displacement during the two earthquakes

Station	Subentry	Peak Acc.(cm/s^2)		Peak Vel.(cm/s)		Peak Dis.(cm)	
		08-5-12	07-01-07	08-5-12	07-01-07	08-5-12	07-01-07
5# (berm)	transverse	27.448	16.810	2.388	-0.451	1.679	-0.0146
	longitudinal	22.828	-15.120	2.295	0.543	0.875	-0.0241
	vertical	-27.116	-12.585	1.378	0.363	-0.833	0.0130
4# (crest)	transverse	-43.995	-	2.951	-	-0.844	-
	longitudinal	-30.642	-	-2.271	-	0.791	-
	vertical	-19.586	-	1.489	-	-0.452	-
11# (crest)	transverse	-	-42.864	-	0.862	-	-0.0231
	longitudinal	-	-29.352	-	-0.635	-	0.0228
	vertical	-	-23.868	-	0.438	-	0.0115

3.2.4 *Acceleration distribution*

Figure 6 shows the maximum distribution of acceleration on the biggest section along the downstream surface. The maximal accelerations in transverse and longitudinal direction decrease first and then increase as the height rising. There are extremums at the crest and the toe of the dam and the acceleration of the toe is even larger. In vertical direction, the maximal acceleration increases first and then falls down with the increasing height. An extremum appears at the 5# station. From the point of each component, except for 5# station, the transverse acceleration is basically larger than those in the other directions and the vertical acceleration is the minimal one.

As the two seismographs on right abutment were in maintenance, no record can reveal the response difference between the left and right abutments during Wenchuan earthquake. The response law can only be concluded according to the past records. Figure 7 shows the maximum distribution of acceleration on dam crest along the axis of dam during the earthquake on Oct.23, 2007. It is obvious that the maximal acceleration of the dam crest increases along with the increasing of the section number, it increase gradually from the left bank to the right.I n detail, the increasing gradient is large from the main dam's biggest section to the beginning of the auxiliary dam, but tiny along auxiliary dam's crest.

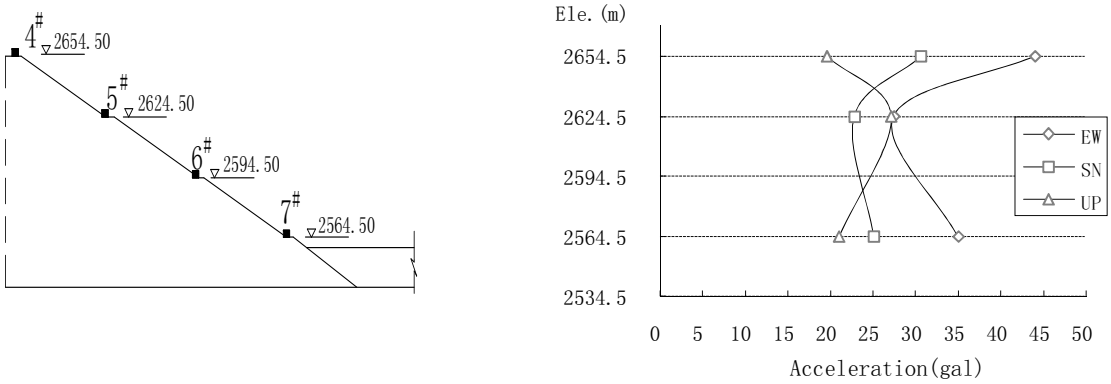


Figure 6 Distribution of acceleration on biggest section along the downstream slope surface on May 12, 2008

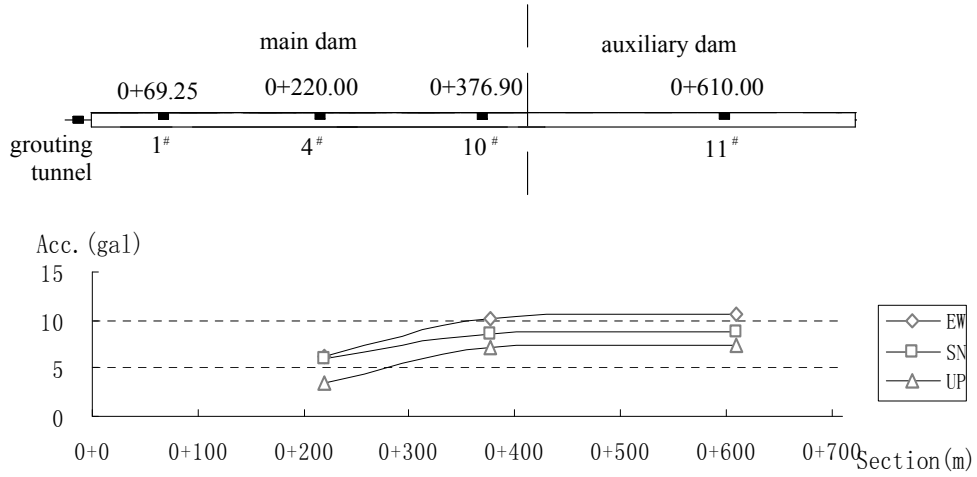


Figure 7 Distribution of acceleration on crest along dam axis during the earthquake on May 23, 2007

According to the dynamic response laws of the YeLe dam analyzed above and associated with the geological condition and the dam structure, it is obtained that the severe dissymmetric distribution of the covering layers have obvious influence on the dynamic response of the dam. As the covering layers deepen gradually from the left abutment to the right and the surface of the underlying bedrock is steep dipping towards the river, the maximal acceleration observed by seismographs increase from the left to right. And the value of the longitudinal acceleration is close to that of the transverse acceleration. Moreover, the seismic response is amplified from the inner to the outer surface of the dam. Thus the extremums arise on the dam crest and the dam toe. Taken the acceleration of dam bottom center for base, the amplification of the earthquake acceleration is 3.14 along the dam height while the one is 2.50 along the dam width.

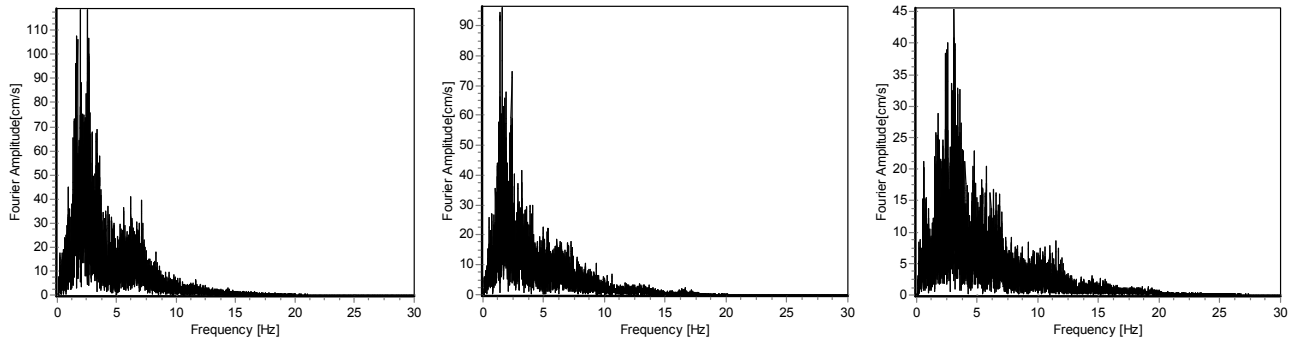
3.3 The Spectral Analysis

3.3.1 Fourier spectrum characteristics

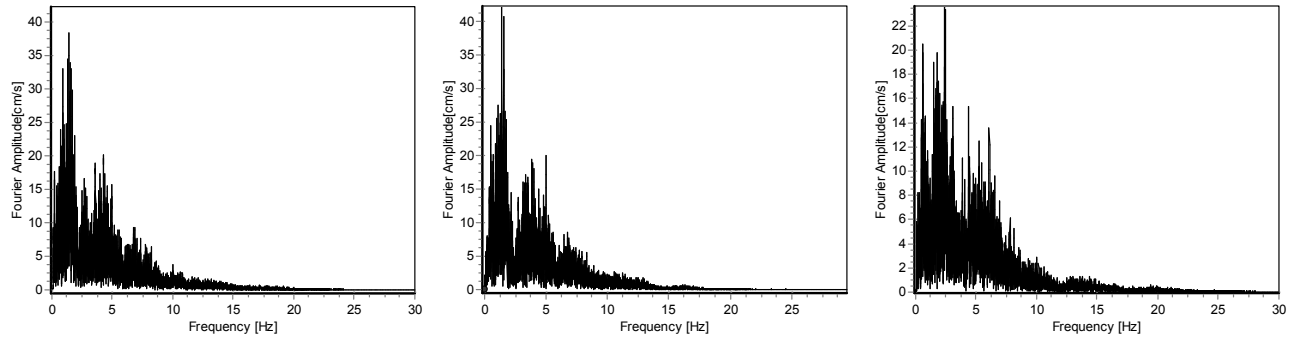
The Fourier spectrums obtained at 4#、13#和 12# stations are shown in Figure 8. As seen from the figure (a), the dam crest's acceleration spectrums have prominent peak between 1-4 Hz, secondary peak between 5-7 Hz and low spectral values at more than 8-10 Hz. The dominant frequency is about 1.5-3 Hz. The secondary peaks are much smaller than the prominent ones. As shown in figure (b), the prominent peak of acceleration spectrums of

dam bottom middle occurs between 0.5-2 Hz, secondary peak between 4-5 Hz and low spectral values at more than 8-10 Hz. The difference between prominent peak and secondary peak is smaller than that of the dam body. The dominant frequency is about 1-2 Hz. From figure (c), the acceleration spectrums of grouting gallery on left abutment have prominent peak between 0.5-4 Hz, no secondary peak and low spectral values at more than 8-10 Hz. The dominant frequency is about 0.5-1 Hz.

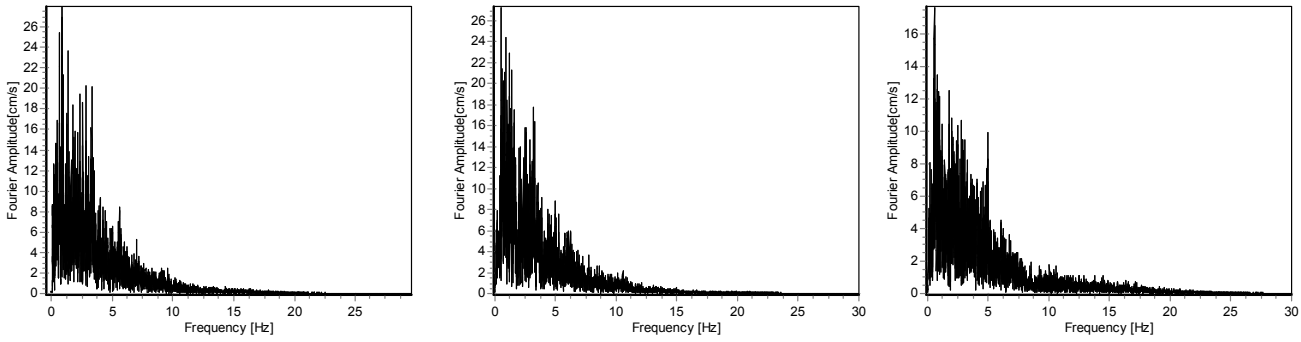
Contrast figure (a) with figure (b), it is shown that the dominant frequency of dam crest is higher than that of dam bottom and the motion is obviously amplified between 1.5-3.0 Hz. In addition, the band of vertical acceleration is wider than horizontal ones.



（a）4# station



（b）13# station



（c）12# station

Figure 8 Fourier spectrum in transverse, longitudinal and vertical direction during the 5.12 Wenchuan Earthquake

3.3.2 *Dominant frequency*

Table 5 The dominant frequency during the three earthquakes (Hz)

Station	Subentry	06-12-16	07-10-23	08-5-12
5# (berm)	transverse	6.25	7.84	1.395
	longitudinal	6.25	5.08	1.633
	vertical	7.57	5.86	2.881

Table 5 lists the dominant frequencies of 5# station during three earthquakes. Compared with the previous two earthquakes, the dam's acceleration spectrums of Wenchuan Earthquake have evident features of narrow band and low dominant frequency. The results of spectrum analysis in Wenchuan Earthquake are given in Table 6. The dominant frequencies of the dam in three directions are higher than those of the bedrock. And dominant frequencies in vertical direction are evidently larger than those in horizontal direction.

Table 6 The spectral analysis results of dam's each position during the 5.12 Wenchuan Earthquake

station	Subentry	dominant frequency (Hz)	dominant period (s)	Fourier amplitude (cm/s)
4# (crest)	transverse	1.923	0.520	118.587
	longitudinal	1.633	0.613	94.045
	vertical	3.120	0.321	45.438
5# (berm)	transverse	1.395	0.717	81.680
	longitudinal	1.633	0.613	67.807
	vertical	2.881	0.347	42.389
7# (berm)	transverse	2.386	0.419	58.987
	longitudinal	2.048	0.488	67.239
	vertical	2.637	0.380	34.476
12# (Grouting Gallery)	transverse	0.916	1.092	28.112
	longitudinal	0.488	2.048	27.217
	vertical	0.555	1.800	17.638
13# (Inspecting Gallery)	transverse	1.395	0.717	38.416
	longitudinal	1.395	0.717	42.332
	vertical	2.356	0.426	23.551

4 THE EFFECT ON THE YELE DAM OF WENCHUAN EARTHQUAKE

4.1 Observed Damage

No abnormal phenomenon was found due to the earthquake. Although the earthquake was quite strong, no crack or dent existed on the surface of the dam. The original crack of parapet on dam crest remained no change and the monitoring posts were not damaged. No water seepage, piping, soil flow occurred near the dam toe. No rocks fell and no landslide on the abutments. But the seepage discharge of a drain hole in drainage gallery on

right abutment seemed a bit more and the flux was about 2.00 L/s.

4.2 Deformation

The effect of the earthquake on dam body, core and diaphragm's deformation was little. After the earthquake, most observation points had the tendency of moving towards the upstream. The largest displacement occurred at dam crest in the downstream of the core with the magnitude of 6.93 mm. In vertical direction, the upper part of the dam settled whiles the lower part uplifted. The largest displacement towards the upstream of the core after the earthquake was 3.87 mm while it was 6.78mm towards the downstream. For the concrete diaphragm the displacements were 2.81mm and 11.14mm towards the upstream and downstream respectively. Based the measured data, the core's junction with transient zone, the joints between the core base and abutments had no change during the earthquake. The joints between the core base and diaphragm were basically closed.

4.3 Seepage

The seepage-proof system on left abutment performed well. The seepage pressure at the upstream of the cut-off wall varied with the reservoir level and the pressure at the downstream of the wall had no change basically. The measured water level in left abutment changed little before and after the earthquake, which indicated the little effect on the left abutment of the earthquake. But the water level of GY10, which was located in the edge of the grouting curtain in left abutment, raised 3.5 m. This might due to the new seepage passage or the lager original seepage passage induced by the earthquake. From the data of osmometers, observation well and seepage around abutment in the right abutment, the seepage pressure also changed little on the whole. Meanwhile, the seepage pressure in the upstream of the cut-off wall in river bed varied with the reservoir level and the pressure in the downstream of the wall didn't. The total seepage discharge in the downstream of the dam changed a little and the seepage discharge on May 29 was 95.37L/s.

4.4 Stress and Strain

The compressive strain of the core increased after the earthquake. Most strain gauges changed between - 40 μ ε ～39 μ ε after the shock and the measured values reached stable gradually. The compressive stress of the substrate in riverbed was greater than that in both abutments and was not affected by the earthquake. The measured values of strain gauges of the substrate fluctuated a little after the earthquake and then also became stable. However, the stress of reinforcements in substrate swings little. Especially at the largest cross section of dam body, the tensile stress increased while the compressive stress decreased. But they rebound later on. The stress of concrete diaphragm was basically compressive and fluctuated a little before and after the earthquake.

4.5 Dam Safety Against Earthquake

Based on the analysis above, the result of inspecting is in gear and no abnormal phenomenon was found. Although the seismic durations are quite long, the response is relatively small. The seismic response law was corresponding to the geological condition. And the pre-seismic and post-seismic monitoring data shows that the deformation, seepage and stress and strain of the dam were affected slightly. Therefore, although there are some exceptional values in certain instruments, the dam remains a normal working state after the great earthquake.

5 CONCLUSIONS

(1) The duration of the seismic recording of the Yele Dam in Wenchuan Earthquake is quite long up to 200s, which is rare in past dam's earthquake record dada. Different positions on the dam have different duration. The peak times of dam's accelerations in the spatial three directions are not coincident and differences exist in the peak time of acceleration of each position.

(2) The dam's seismic response is small. The seismic response is amplified from the inner to the outer surface of the dam. Thus the extremums arise on the dam crest and the dam toe meanwhile. And the dissymmetric foundation geological conditions lead to the dissymmetric seismic response distribution between the abutments.

(3) Compared with the past records, the dam's respond velocity and displacement are obviously larger during Wenchuan Earthquake.

(4) As to the dam, the amplification of the earthquake acceleration is 3.14 along the dam height while along the dam width is 2.5.

(5) The dam's acceleration spectrums of Wenchuan earthquake show features of narrow band and low dominant frequency. The dominant frequencies of the dam body in three directions are higher than those of the bedrock. The motions between 1.5-3.0 Hz are obviously amplified. Finally the dominant frequencies in vertical direction are evidently larger than those in horizontal direction.

(6)Based on the time-history analysis and combined with the inspecting and the analysis of the deformation, seepage, stress and strain data, the Yele Dam remains an normal working state after the 5.12 Wenchuan Earthquake.

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