Seismic Response Characteristics of Earth and Rockfill Dams

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SUMMARY:
With the development of theories and construction technologies, more and more well-compacted high rockfill dams (200 m even 300 m high) have been built and are being planned worldwide. The seismic response of an earth or rockfill dam, especially the maximum acceleration at dam crest, is one of the most important engineering properties for dam design and safety evaluation after earthquake. An extensive review of case histories of earth and rockfill dam behaviour during earthquake was undertaken in this study. The peak crest accelerations and peak ground accelerations from 43 case histories were summarized. Results from finite element analyses of 6 typical dams and 12 practical projects of modern high rockfill dams were also presented. Due to the improvement in quality of rockfill compaction by modern advanced compacting technology, well-compacted rockfill dams behave differently from those of early earth-rockfill dams. Therefore, the case histories are classified into two categories: well-compacted rockfill dams and early earth-rockfill dams. The effect of dam height on the seismic response distribution is discussed. An empirical equation was proposed for preliminarily estimating the seismic response of a well-compacted rockfill dam according to the case history records. Effects of dam height, narrowness of canyon, seismic motion input, angle of incidence, shear modulus of the rockfill material and slope gradient on the peak crest acceleration of a rockfill dam are discussed according to numerical analysis results.

Keywords: Earth dam; Rockfill dam; Seismic response; Earthquake engineering

1. GENERAL INSTRUCTIONS

Many engineers assume that well-compacted rockfill dams have a high resistance to seismic loading, according to acceptable past performance of similar dams (Bureau 1985). However, as the number of high rockfill dams under construction increases worldwide, the issues of seismic safeties of the affiliated structures, rather than dam body rockfill materials, become of vital importance. These affiliated structures include: clay or asphalt concrete cores for earth core rockfill dams (ECRDs), concrete face slabs for concrete face rockfill dams (CFRDs), water retaining and release structures such as spillways, monitoring systems, water and power supply facilities, etc.

A recent reminder of the need to improve our understanding of the affiliated structures is Wenchuan earthquake (M = 8) that shook the 156-m-high Zipingpu dam (China) on May 12, 2008. The strong earthquake caused significant cracks in the face slabs, severely damages to the buildings on the dam, and damages on structures include the winch and hoisting devices for the tunnel spillways, some devices of the gantry crane for power tunnel, the transmission frameworks and the insulation, and the set bolts of the closed switch gears (Guan 2009). However, considering that the dam was designed for a peak ground acceleration of only 0.26 g, Zipingpu dam behaved remarkably well during and after the very strong shaking with a peak bedrock acceleration ≥ 0.5 g. Soon after the earthquake, the damage was repaired and the dam became operational again.

The damages of the affiliated structures related closely to the seismic behaviour of the dam body in two aspects: a), permanent deformation of the dam body due to the earthquake causes unrecoverable cracks in face slabs and uneven settlements for on dam buildings; and b), amplified accelerations increases the inertial loadings for the structures. Case histories of permanent deformation of earth and rockfill dams has been presented by (Swaisgood 2003). This paper only focuses on the latter aspect, i.e., the seismic response (peak crest acceleration and acceleration distribution) of earth and rockfill dams.

The seismic response of an earth or rockfill dam depends on a large number of factors, such as the quality of rockfill compaction, the dam geometry, the narrowness of the canyon, the irregularity of the abutment, the flexibility of the canyon rock, the ground motion intensity, its frequency characteristics, spatial variability, etc (Dakoulas 2012). Evaluations of seismic behaviour of earth or rockfill dams have relied mostly on site investigations (Elgamal 1990), theoretical and numerical analyses (Gazetas 1992; Uddin 1995; Uddin 1999; Seiphoori 2011; Zou 2011), and shaking table tests (Han 1988; Kim 2011). Harder (Harder 1998) summarized more than 20 case histories of earth and rockfill dams experienced earthquakes and presented the relationship of peak crest accelerations against peak ground accelerations. However, due to the development of modern advanced compacting technology, rockfill dams built after - 1968 obviously have more resistances to earthquake than early earth-rockfill dams, which results in differences in the seismic response characteristics of these two dam types.

In this study, an extensive review of case histories of earth and rockfill dam behaviour during earthquake was carried out. The peak crest accelerations and peak ground accelerations from 43 case histories and 18 numerical analyses were summarized. Efforts have been made to find out if there is a trend of seismic response that can be predicted, and if there are certain factors that consistently have an effect on the value of peak crest acceleration during earthquakes. The differences in seismic response characteristics between early earth-rockfill dams and well-compacted dams are discussed.

2. SEISMIC RESPONSES OF DAMS

The peak crest accelerations and peak ground accelerations from case histories are summarized in Table 1. According to the property of filling materials, the data are classified into two categories: A, earth dams or early built (before 1968) earth-rockfill dams; B, lately built (after 1968) well-compacted rockfill dams. Although La Villita dam consisted of well-compacted rockfills (Resendiz 1982), it was classified into Category A because of its 75 m thick alluvial deposits. Finite element results of 18 dams, which include 7 from unpublished research reports of modern well-compacted high rockfill dams in China by the authors, are presented in Table 2.

Table 1. Accelerations at dam crest from case histories

No	Name	Location	Dam Type	DH m	CL m	Earthquake Date	Built year	PGA g	PCA g	AFC	Reference
Category A: earth dams and early (before 1968) earth-rockfill dams											
1	Baihe	China	E	66	960	7/28/1976	1960	0.053	0.128	2.42	(Shen 1981)
2	Cogswell	USA	CFRD	85.3	175	10/1/1987	1935	0.064	0.151	2.36	(Boulanger 1993; Boulanger 1995)
3	Cogswell	USA	CFRD	85.3	175	10/1/1987	1935	0.064	0.151	2.36	(Boulanger 1993; Boulanger 1995)
4	Del Valle	USA		67.7		10/17/1989		0.04	0.08	2.0	(Harder 1998)
5	El Infiernillo	Mexico	ECRD	148	350	3/14/1979	1963	0.105	0.355	3.38	(Resendiz 1982)
6	Ishibuchi	Japan	CFRD	53	345	5/26/2003	1953	0.147	0.268	1.82	(Nagayama 2004)
7	Kawanishi	Japan	E	43	170	10/23/04	1978	0.56	0.58	1.04	(Yasuda 2005)

8	La Villita	Mexico	ECRD	60+75[1]	497	10/11/1975	1967	0.073	0.348	4.77	(Elgamal 1990)
9	La Villita	Mexico	ECRD	60+75[1]	497	11/15/1975	1967	0.041	0.204	4.98	(Elgamal 1990)
10	La Villita	Mexico	ECRD	60+75[1]	497	3/14/1979	1967	0.083	0.39	4.69	(Elgamal 1990)
11	La Villita	Mexico	ECRD	60+75[1]	497	10/25/1981	1967	0.087	0.42	4.95	(Elgamal 1990)
12	La Villita	Mexico	ECRD	60+75[1]	497	9/21/1985	1967	0.042	0.21	5.00	(Elgamal 1990)
13	Leroy Anderson	USA	ECRD	71.6	436	4/24/1984	1950	0.41	0.63	1.54	(Bureau 1985)
14	Leroy Anderson	USA	ECRD	71.6	436	10/17/1989	1950	0.26	0.43	1.65	(Harder 1998)
15	Lexington	USA	E	62.5	247	10/17/1989	1953	0.45	0.45	1	(Harder 1998)
16	Long Valley	USA	E	60	184	5/ /1980		0.17	3.06	0.52	(Gazetas 1987)
17	Los Angeles	USA	E	47		1/17/1994		0.28	0.43	1.54	(Harder 1998; Swaisgood 2003)
18	O'Neill	USA	E	21.3		10/17/1989	1967	0.008	0.14	1.75	(Harder 1998)
19	Oroville	USA	E	235	1707	8/1/1975	1968	0.1	0.12	1.2	(Bureau 1985)
20	San Luis	USA	E	95.4		10/17/1989	1967	0.04	0.19	4.75	(Harder 1998)
21	Santa Felicia	USA	E	83.3	389	9/2/1971	1955	0.217	0.207	0.954	(Abdel-Ghaffar 1979)
Category B: lately built (after 1968) well-compacted rockfill dams											
22	Kisenyama	Japan	ECRD	95	255	9/ /1969	1969	0.01	0.1	10	(Gazetas 1987)
23	Kuzuryu	Japan	ECRD	127.7	355	9/ /1969	1968	0.02	0.04	2.0	(JEPCETA 1986)
24	Matahina	New Zealand	ECRD	86	400	3/2/1987		0.24	0.35	1.45	(Pender 1987)
25	Miho	Japan	ECRD	95	588	1/29/1980	1978	0.031	0.066	2.45	(Iwashita 1995)
26	Miho	Japan	ECRD	95	588	4/14/1981	1978	0.031	0.087	2.8	(Iwashita 1995)
27	Miho	Japan	ECRD	95	588	8/8/1983	1978	0.148	0.257	1.74	(Iwashita 1995)
28	Miho	Japan	ECRD	95	588	2/17/1987	1978	0.011	0.066	5.96	(Iwashita 1995)
29	Miho	Japan	ECRD	95	588	8/5/1990	1978	0.028	0.080	2.87	(Iwashita 1995)
30	Miho	Japan	ECRD	95	588	2/2/1992	1978	0.012	0.032	2.65	(Iwashita 1995)
31	Nagara	Japan	ECRD	52	250	12/17/1987	1985	0.262	0.369	1.408	(Tani 2000)
32	Otani	Japan	RD	75.5	360	10/23/2004	1993	0.062	0.195	3.14	(Yasuda 2005)
33	Oya	Japan	ECRD	56.5	240	2/7/1993	1992	0.066	0.193	2.93	(Iwashita 1995)
34	Oya	Japan	ECRD	56.5	240	2/8/1993	1992	0.007	0.038	5.67	(Iwashita 1995)
35	Oya	Japan	ECRD	56.5	240	2/16/1993	1992	0.098	0.03	3.02	(Iwashita 1995)
36	Oya	Japan	ECRD	56.5	240	2/22/1993	1992	0.014	0.053	3.69	(Iwashita 1995)
37	Oya	Japan	ECRD	56.5	240	12/8/1993	1992	0.004	0.015	3.42	(Iwashita 1995)
38	Oya	Japan	ECRD	56.5	240	6/7/1994	1992	0.005	0.01	2.08	(Iwashita 1995)
39	Sagurigawa	Japan	ECRD	119.5	420	10/23/2004	1993	0.046	0.146	3.174	(Yasuda 2005)

40	San Justo	USA	ECRD	41	340	10/17/1989	1986	0.26	0.4	1.53	(Harder 1998)
41	Takami	Japan	ECRD	120	435	9/26/2003	1983	0.058	0.325	5.62	(Nagayama 2004)
42	Zipingpu	China	CFRD	156	635	5/12/2008	2006	0.55[2]	1.65/0.8[2]	1.6	(Guan 2009; Kong 2010)
43	Zipingpu	China	CFRD	156	635	11/6/2008	2006	0.034	0.08	2.4	(Kong 2011)

Note: 1. There's a 75 m alluvial deposit layer under La Villita dam.
2. A peak acceleration of 1.65 g was recorded along stream direction by the observation stations on Zipingpu dam. However, the peak acceleration reduces to 0.8 g after filtering the high-frequency components of the acceleration response. The latter value of 0.8 g was believed to be the reasonable value of the peak crest acceleration of Zipingpu dam during Wenchuan earthquake (Kong 2010). The monitoring stations failed to record the PGA at dam site. The value of 0.55 g was estimated according to a large amount of analyses (Kong 2010).

Table 2. Accelerations at dam crest from numerical analyses

No	Name	Location	Dam Type	DH m	CL m	PGA g	AFC	$AF^{1/5}$	Reference
1	A typical dam		CFRD	100	300	0.49	3	2	(Seiphoori 2011)
2	A typical dam		CFRD	100	2D	0.69	2.23	1.45	(Uddin 1995)
3						0.6	2.43	1.78	(Uddin 1995)
4						0.42	2.1	1.79	(Uddin 1995)
5						0.37	2.27	1.38	(Uddin 1995)
6						0.36	1.72	1.0	(Uddin 1995)
7	Cogswell	USA	CFRD Category A	85.3	2D	0.064	2.97-4.53		(Boulanger 1993)
8				85.3	2D	0.264	1.33-2.58		(Boulanger 1993)
9	Houziyan	China	CFRD	223.5	283	0.3	3.5	2.0	Unpublished report
10	Liangfengtai	China	CFRD	100	257	0.146	3.2	2.6	Unpublished report
11	Lianghekou	China	ECRD	295		0.29	2.6	1.17	Unpublished report
12	Longpan	China	ECRD	266	734	0.407	2.3	0.81	Unpublished report
13	Messochora	Greece	CFRD	150	330	0.35	3.9	2.43	(Dakoulas 2012)
14	Shuangjiangkou	China	ECRD	312	584	0.205	3.9	1.61	Unpublished report
15	Wenquan	China	CFRD	102	306	0.171	3.7	2.63	Unpublished report
16	Wuyi	China	ECRD	102.5	464	0.22	3.3	1.59	Unpublished report
17	Zipingpu	China	CFRD	156	635	0.55	1.6	0.91	(Zhou 2011)
18						0.034	3.0	1.3	(Kong 2011)

Note: Most of the values of $AF^{1/5}$ are estimated form figures.

The abbreviations in the tables and in this paper are,

AFC – Acceleration amplified factor at crest, AFC = PCA/PGA;
$AF^{1/5}$ – Acceleration amplified factor at top 1/5 height of the dam;
CFRD – concrete face rockfill dam;
CL – Crest length;
DH – Dam height;
E – Earth dam.
ECRD – Earth core rockfill dam;
PCA – Peak crest acceleration;
PGA – Peak ground acceleration;

3. ANALYSIS AND DISCUSSION

3.1. Seismic response characteristic of modern high well-compacted rockfill dams

Modern compacting technology can densify the rockfill material to a dry unit weight of 2.1 - 2.2 g/cm^3. While the dry unit weight is about 1.7 - 1.8 g/cm^3 for dumped rockfills and 1.8 - 1.9 g/cm^3 for early compacted rockfills, such as of El Infiernillo dam (Resendiz 1982). Well-compacted rockfill materials have a higher shear modulus, thus have a higher resistance to seismic loading than early earth and rockfill dams. This results in differences not only in the value of AFC, but also in the distribution of acceleration along the vertical dam axis. It is necessary to keep in mind the differences in the seismic response between earth and well-compacted rockfill dams before analyzing the case history data.

Most earth dams are lower than 50 m and have a smaller shear modulus. While most well-compacted rockfill dams in the case histories are - 100 m in height. Some latest built or planning rockfill dams reach 200 m even 300 m high. Figure 1 shows the effect of dam height on the peak acceleration distribution of a rockfill dam from numerical analyses (田村重四郎 1991; Kong 1992). It can be seen that the higher is the dam, the smaller amplified factor (AF) can be found below the top 1/3 to 1/5 area of the dam. But for a higher dam, AF amplifies more obviously at the top area of the dam. That is to say, the higher is the dam, the more obvious is the "whip-lash" phenomenon in the seismic response of rockfill dams.

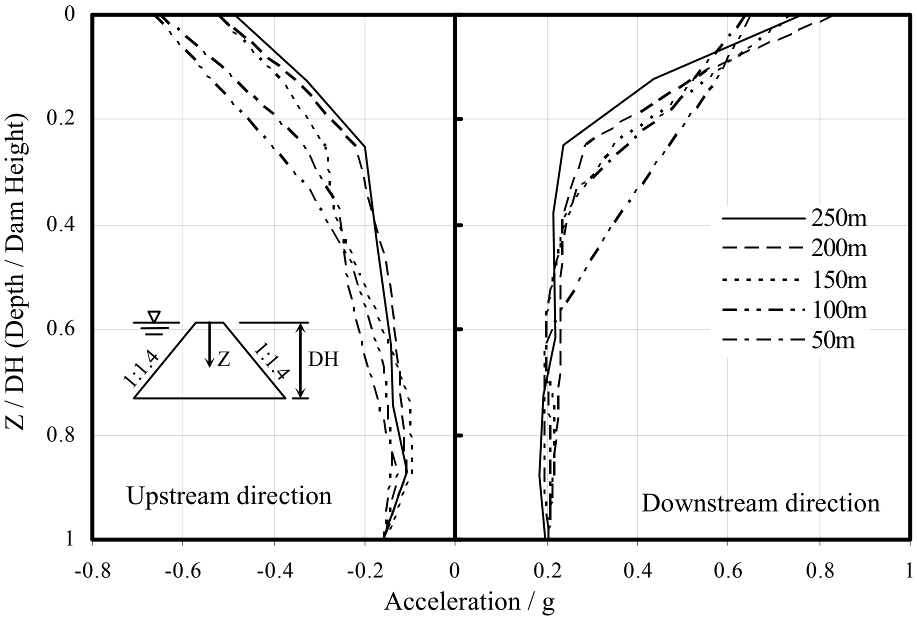

Figure 1. Effect of dam height on the peak acceleration distribution (田村重四郎 1991; Kong 1992)

Considering the characteristic of acceleration distribution, it is evident that measures to improve the performance of high rockfill dams subjected to strong ground shaking should focus on the mid-upper part of the dam, such as: (a) use of a flat slope in the upper part (top 1/3 to 1/5), to reduce high deformations and avoid surface rockfill instability; (b) use of a wide crest to improve safety under high accelerations and reduce the effects of any crest settlements due to rockfill sliding at the downstream face; and (c) strengthening of slopes in the upper area of the dam.

3.2. Acceleration amplified factor at crest centre from case histories

As mentioned above, the seismic response of an earth or rockfill dam depends on a large number of factors. Due to the varieties in those factors for various dams, it is difficult to find out the effect of each factor on the characteristic of seismic responses of earth or rockfill dams from case histories. However, the acceleration amplified factor at crest (AFC) show a relatively clear trend to the value of PGA, as shown in Figure 2. It can be seen in general that the value of AFC decreases with increasing PGA.

The AFC results of well compacted rockfill dams and those of early earth-rockfill dams are marked by solid dots and hollow marks respectively. For rockfill dams suffered strong earthquakes (PGA > 0.1), all the AFC values are lower than 2.0, which showed good performances of rockfill dams under seismic loading. For rockfill dams under small shocks, i.e., PGA < 0.1 g, the value of AFC scattered in a large range from 2.0 to 6.0. No obvious relationship between AFC and DH can be found for rockfill dams. The following equation can be used to approximately predict the value of AFC for well-compacted rockfill dams according to the value of PGA,

$$\mathrm{AFC} = \frac{\mathrm{PCA}}{\mathrm{PGA}} = \frac{0.5}{\sqrt{\mathrm{PGA}}} + 1.0 \tag{3.1}$$

where AFC is the amplified factor at crest; PCA is the peak crest acceleration; and PGA is the peak ground acceleration. As shown in Figure 2, Eqn (3.1) forms the upper bound of the AFC values of well-compacted rockfill dams, except one case of Takami dam.

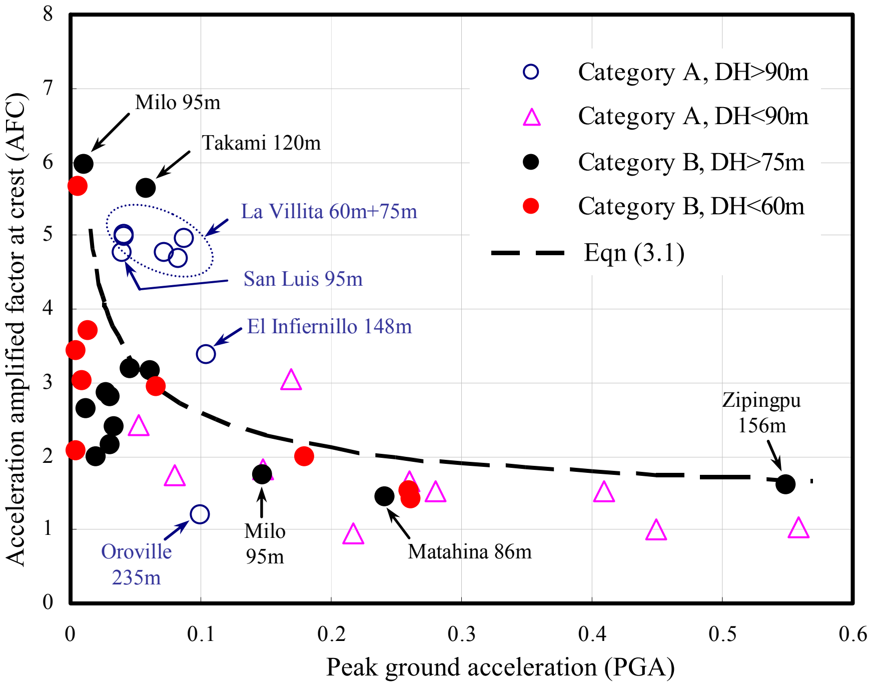

Figure 2. Variation of acceleration amplified factor at crest against PGA from case histories

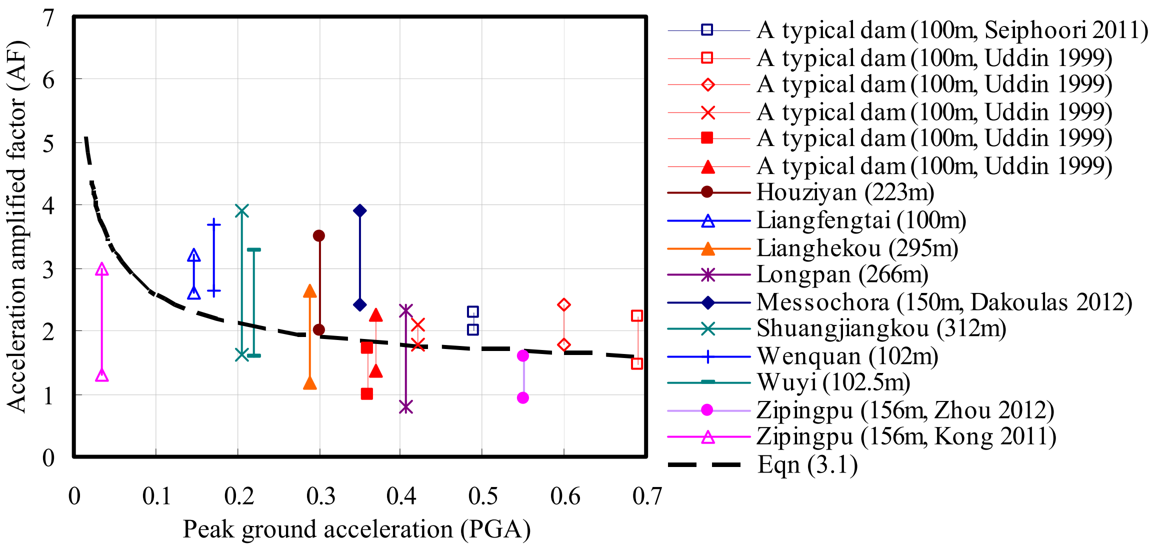

Figure 3. Variation of AF against PGA from numerical analyses
(upper point – AFC; lower point – $\mathrm{AF}^{1/5}$)

3.3. Acceleration amplified factor at crest centre from numerical analyses

Besides of data from case histories, acceleration amplified factors from published numerical analyses are also summarized, as listed in Table 2. The effect of variety in numerical models is not specifically analyzed in this study. The numerical results from modern well-compacted rockfill dams are plotted in Figure 3. As discussed above, the "whip-lash" effect is obvious for modern compacted rockfill dams under strong shaking. Only the top area of the dam experiences extremely high accelerations. Therefore, besides of the value of AFC, the acceleration distribution is also important for estimating the seismic safety of the dam. Therefore, both AFC and $AF^{1/5}$ are plotted in Figure 3 for each case.

Similar to the results from case histories, the values of AFC and $AF^{1/5}$ from numerical analyses also decreases with increasing PGA. However, AF values calculated by Eqn (3.1) are not the upper bound of the values of AFC from numerical analyses. This may be because that the case history results are from 60 to 120-m-high dams mostly built before 1990, while the numerical results are mostly from much higher dams (100 m to 300 m). Besides, the case histories of rockfill dams experienced strong earthquakes are very limited. The "whip-lash" effect may not be excitated during practical earthquakes. Anyway, most of the values of $AF^{1/5}$ are lower than or close to the predictions by Eqn (3.1).

3.3. Effects of other factors on the seismic response of rockfill dams

As mentioned above, the seismic response of an earth or rockfill dam depends on a large number of factors, such as the quality of rockfill compaction, the dam geometry, the narrowness of the canyon, the irregularity of the abutment, the flexibility of the canyon rock, the ground motion intensity, its frequency characteristics, spatial variability, etc. The situation of a dam differs from another, results in difficulties when attempting to analyze the effect of any of the factors on the seismic response of rockfill dams. By contrast, numerical analyses show their advantages to investigate the effect of a specified factor on the seismic response, by changing the value of the factor but keep all the other parameters unchanged. The seismic response characteristics of rockfill dams investigated by numerical analyses can be concluded in Table 3.

Table 3. Effects of some factors on the seismic response of a rockfill dam by numerical analyses

ID	Factors	Effect	Degree
1	Peak ground acceleration (PGA)	An increase in PGA lead to obvious decrease in AFC (Zou 2011). PGA↗ ⇒ AFC↘	Obvious
2	Narrowness of canyon (DH/CL)	A 3D canyon gave higher PCA than 2D plane strain analyses (Gazetas 1987); The results of a 300-m-high rockfill dam with various crest length (CL) showed that the increase of CL from DH/CL = 1:1 to 1:3 decreases the AFC from 3.0 to 2.4 (Zou 2011). CL/DH↗ ⇒ AFC↘	Moderate
3	Seismic motion input	The variation in seismic motion input response (with same derived PGA) has certain effects on the value of PCA due to various frequency characteristic of each input response (Zou 2011).	Moderate
4	Angle of incidence	The maximum response is obtained at an angle θ = 30° - 35° and is about 25% higher than the response caused by vertically propagating waves (Gazetas 1992).	Moderate
5	Dam height (DH)	AFC decreases from 3.5 to 3.0 when increasing DH from 100 m to 300 m, with unchanged slope gradients and the same ground motion input (Zou 2011). DH has obvious effects on the acceleration distribution of a rockfill dam (Kong 1992).	Moderate
6	Shear modulus	The inhomogeneity in shear modulus lead to a reduction in PCA (Gazetas 1987);	Moderate
7	Slope gradient	The results of a 300-m-high rockfill dam with various slop gradients from 1:1.4 to 1:2.0 showed that the slope gradient has minor effects on the value and distribution of AF (Zou 2011).	Minor

4. CONCLUSIONS

This study summarized 43 case histories and 18 numerical analyses of earth and rockfill dam behaviour during earthquake, focusing on the characteristics of seismic response, i.e., the acceleration distribution and peak crest acceleration. Conclusions were drawn in the following:

(a) The peak crest acceleration (PCA) decreases with increasing the peak ground acceleration (PGA). An approximate equation was present to predict the upper bound of PCA of well-compacted rockfill dams according to the results of case histories.
(b) Well-compacted rockfill dams have a higher resistance than early earth-rockfill dams. The higher is the rockfill dam, the more obvious is the "whip-lash" phenomenon.
(c) Both case histories and numerical analyses show that the acceleration amplified factor increases more obviously at the top 1/3 to 1/5 area of the dam in vertical direction and 3/10 area from the crest centre in the axial direction. Aseismic measures for high rockfill dams should focus on the mid-top area of the dam.
(d) The narrowness of canyon, seismic motion input, angle of incidence, shear modulus of rockfill, and dam height have moderate effects on the value of PCA. The dam slope has a minor effect on the seismic response of a rockfill dam.

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