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ORIGINAL PAPER

2008 Hans Cloos lecture. Seismic geo-hazard assessment of engineering sites in China

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Abstract Based on the fault-block concept, the paper proposes a scheme for the seismic geo-hazard assessment of engineering sites. A *general geo-hazard intensity* is determined by comparing the *basic intensity* of the block where the engineering structure is to be located and the *influencing intensity* associated with the potential epicenter of a strong earthquake in the boundary fault zone. The obtained *general intensity* is then modified to take into account the local ground conditions and pre-existing geo-hazard level (particularly landslides) to obtain the *comprehensive intensity*, which is the basis for the seismic geo-hazard level assessment and site planning recommendations. Four dam sites associated with major hydropower stations are discussed, as well as the 100 m high Zipingpo dam which is located close to the epicenter of the Wenchuan earthquake. The results show that a dam designed on an intensity close to that proposed in the paper would be able to resist potential destructive earthquakes without significant distress.

Keywords Seismicity · Fault-block concept · Seismic geo-hazard level · Comprehensive intensity · Seismic geo-hazard assessment

Introduction

Destructive earthquakes are one of the main natural disasters which affect China and have resulted in numerous deaths. The location of China, in the south-east corner of the Eurasian continent, means it is subjected to stresses from two directions: to the south, the Indian Plate (including the Himalayas) and to the east, the Philippine Plate which is part of the Circum-Pacific belt. As a consequence, seismicity is one of most important factors to be considered in the engineering planning and design of major projects in the country.

Based on long experience in engineering geological investigations in seismic regions, the author proposes a practical scheme for the assessment of seismic geo-hazard levels (SGHL) to be taken into account when constructing major projects and urban development in China.

The distribution of the epicenters of strong earthquakes (over Richter scale $M_S = 7.0$) in China gives obvious support to the "Fault-Block Tectonics" first proposed by the Late Professor Zhang (1984) in his study of the regional geology of China. This concept was developed by Li et al. (1987), Li (1991) and Wang et al. (1991, 1994) who applied it to engineering geology. The author should mention that in the development of engineering geology in China in the 1970s a combined structural plane and structural block model has been proposed for the evaluation of rock mass properties and stability analysis (Wang 1966; Gu 1965; Wang 1965; Gu 1979; Gu and Wang 1980, 1982). In general, the "Fault-block concept" and "Structural plane-block model" are understood to be the control mechanism for movements in the earth's crust and the deformation experienced at different terrain scales.

Based on the fault-block concept, the author has proposed a seismic geo-hazard assessment scheme based on a comprehensive intensity (I_S) measure for assessing the SGHL at engineering sites. This intensity is evaluated from both the seismic faults and terrain blocks, taking into account the ground conditions and the original landslide hazard level, as well as the importance of the project. From

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this evaluation, recommendations can be made for both site planning and project design, including a seismic acceleration factor and SGHL class.

This paper discusses the application and calibration of the proposed scheme based on the analyses of four dam sites: the 180 m high gravity dam in the Three Gorges area, the 240 m high Ertan arch dam; the 162 m high Xiangjiaba gravity dam and the 278 m high Xiluodu arch dam. The first two dams have been completed and the others are under construction. Bearing in mind the high risks involved in these projects, a conservative parameter for seismic acceleration was adopted in the design for all four dams. The results obtained in the SGHL assessment gave a similar solution, reflecting the very high potential hazard level.

The paper also includes a discussion of the seismic behavior of the Zipingpo dam, located in the epicenter area of the $M_S = 8.0$ (Richter scale recorded by the national seismograph network) Wenchuan earthquake of May 12, 2008. The 132 m high Zipingpo dam is a concrete plate rock fill construction and was slightly damaged in the earthquake. Although the design acceleration ($g = 0.26$) was less than the loading by the seismic motion, the slopes did not fail as they were reinforced and protected by prestressed anchors.

Seismicity of China

China often experiences strong earthquakes. Indeed, the frequency, magnitude and the associated fatalities are amongst the highest in the world.

The first destructive earthquake was recorded in 320 BC at Shanxi by ancient Chinese Horn–Born caligraphy. Since then, some 60 destructive earthquakes over magnitude 7 have been documented, although clearly this is an incomplete record. Some of these earthquakes cause huge numbers of deaths; for example, in 1303 some 48,000 fatalities are recorded at the time of the M 8 (estimated by field study of ancient earthquake in correlation with Richter scale) Shanxi Hongdong earthquake. Prior to the 1900s, the largest number of fatalities recorded was in 1556 when 83,000 died associated with the >M 8 Shanxi Huaxian earthquake (Guo and Ma 1988). Most of the large death tolls were in the area of the Yellow River basin of Central China, which was densely populated in ancient/historic times.

In the last century, 15 earthquakes with a magnitude >7 have been recorded in mainland China (Table 1). The statistics show that over 750,000 people died during these 15 earthquakes, with 240,000 deaths recorded for the M_S 7.8 Tangshan earthquake in 1976. The May 12, 2008 Wenchuan earthquake of M_S 8.0 resulted in 87,149 deaths and 374,643 injured.

According to the latest statistics, 62% of all deaths associated with natural disasters are related to the effect of earthquakes. As a consequence, it is important that engineering geologists study the location and possible devastation resulting from earthquakes and for some time work on seismic geo-hazard assessment has attracted the most prominent engineering geologists in the country.

Figure 1 shows the distribution of most of the recorded earthquakes up to the beginning of the 21st century. Comparing Figs. 1 and 2, it can be seen that, as expected, the most destructive earthquakes (M 7–8 and over) are located along major seismically active fault zones.

As a result of the movement of the Indian Plate northwards toward the Himalayas, the terrain in western China is

Table 1 Extreme seismic hazards since 1900 in China mainland

No.	Date	Location	Magnitude (M)	Epicenter intensity (I_E)	Fatalities
1	1902	Ashitu, Xinjiang	8.25	XI	1,000
2	1904	Daofu, Sichuan	7	IX	>400
3	1906	Shawanxi, Xinjiang	7.7	X	>300
4	1908	Qiling Lake, Tibet	7	IX	<100
5	1920	Haiyuan, Ningxia	8.5	XI	240,000
6	1927	Gulong, Gansu	8	XI	40,000
7	1932	Changma, Gansu	7.6	X	70,000
8	1933	Maoxian, Sichuan	7.5	X	20,000
9	1950	Chayu, Tibet	8.5	XII	4,000
10	1966	Xintai, Hebei	7.2	IX	8,064
11	1970	Tonghai, Yunnan	7.7	X	15,621
12	1975	Haicheng, Liaoning	7.3	IX	1,328
13	1976	Tangshan, Hebei	7.8	XI	242,000
14	1988	Lancong, Yunnan	7.6	IX	743
15	2008	Wenchuan, Sichuan	8.0	XI	87,149

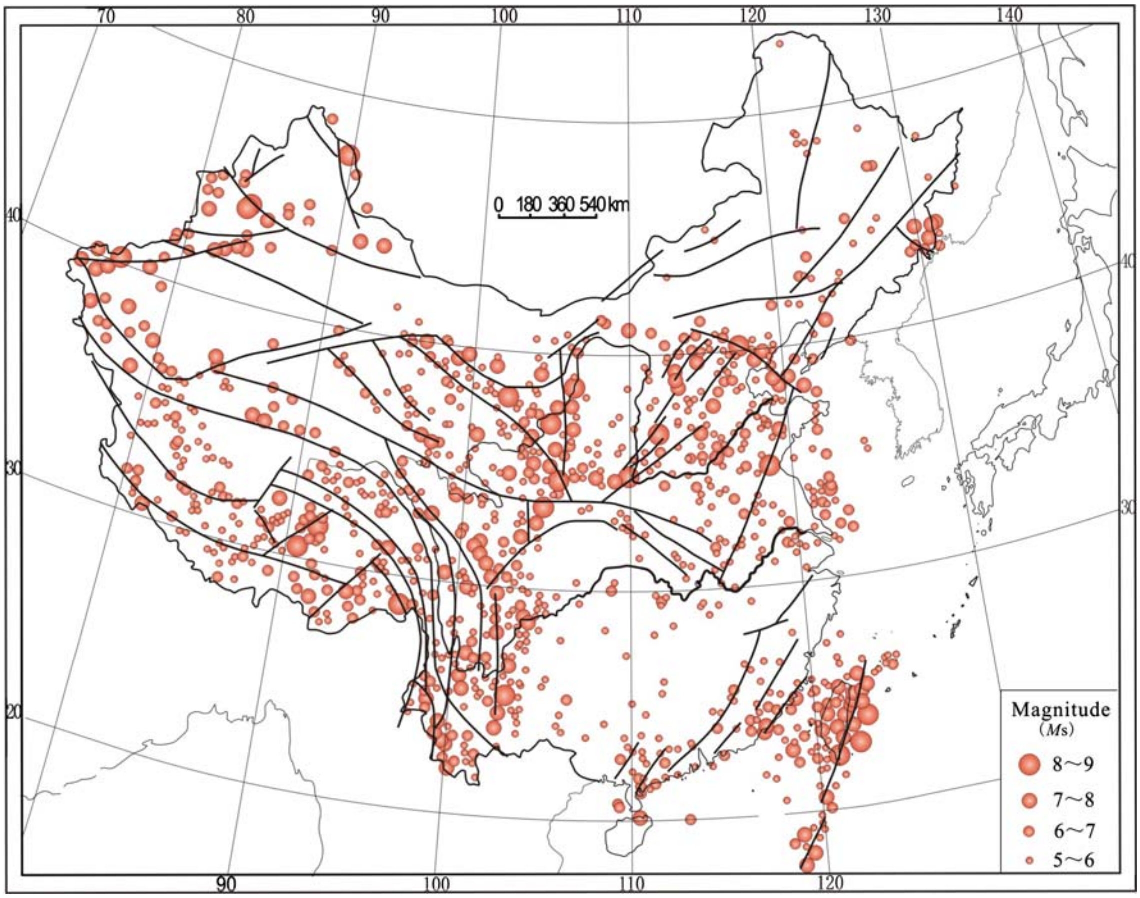

Fig. 1 Earthquake epicenter distribution of China (2300B.C.–2000A.D., Richter scale $M \geq 5$)

being subjected to intense deformation. Most of the deep-seated faults in this area are still experiencing tectonic movement, resulting in strong earthquakes. The compressive stress at the eastern boundary of the Indian Plate where it abuts mainland China results in under–crustal plastic flow and the formation of prominent south-north tectonic fractures.

In northern China, subduction of the Pacific Plate beneath the Eurasian Plate subjects the crust to "stretching" (tensional) deformation, resulting in normal or lateral fault movement and some strong earthquakes.

To the south and south-east of China, the northwestern movement of the Philippine Plate has an important effect on Taiwan and the coastal area of Fujian (Fig. 2). However, as the plate margin is to the east of mainland China, the global stresses do not directly affect south east China, hence that area has relatively less seismicity.

In general, the location of China with respect to the earth's plates means that seismic activity must be expected to continue in the western and northern areas and in the island of Taiwan to the south east.

Fault-block concept of seismic geo-hazard formation

Based on the study of the distribution of mineral deposits, magmatic rock belts and seismic zones, the late Professor Zhang Wenyou proposed a fault-block concept to explain the geotectonic patterns and crustal movement in China. This theory is comprehensively discussed in his monograph entitled *Introduction to Fault-Block Tectonics* (Zhang 1984).

Li et al. (1987), Li (1991) and the author (Wang et al. 1991, 1994) accepted the fault-block concept in seismic risk studies. As shown in Fig. 3, the epicenters of >M7 earthquakes are largely located on the major fault zones while much lower seismicity is observed between the seismic fault zones.

Gu and colleagues (Gu 1979; Gu and Wang 1980, 1982) proposed an engineering geomechanical approach and a rock mass structure model consisting of structure plane and structure blocks was adopted in the engineering geological evaluation of rock mass stability and regional crustal stability.

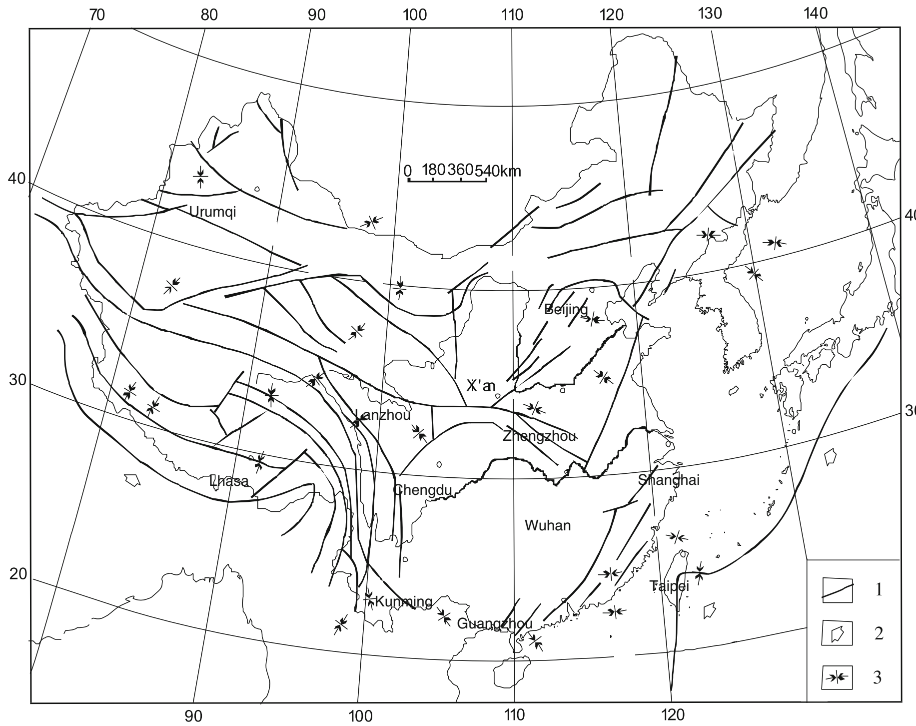

Fig. 2 Fracture pattern and crustal loading conditions of China. *1* Major faults, *2* Direction of plate movement, *3* Orientation of maximum principal geo-stress

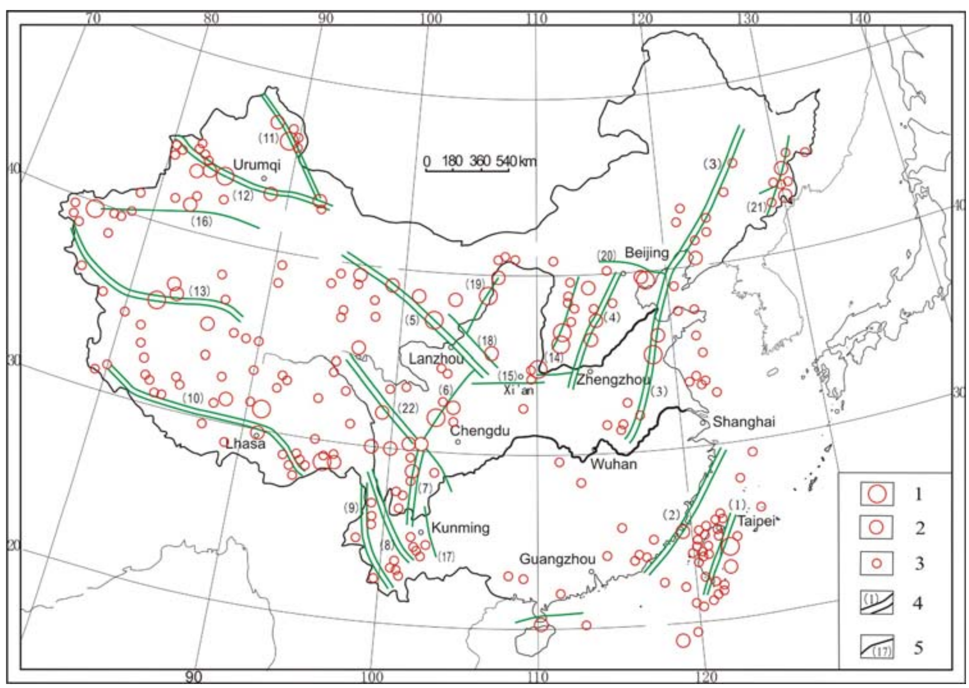

Fig. 3 Seismic fault zones in China (Li et al. 1987). *1* $M > 8$, *2* M =7–8, *3* M = 6–7, *4* Lithosphere faults, *5* Crustal faults, Fault numbers referred to in Table 3

In the fault-block system two kinds of seismic sources are distinguished, i.e., epicenters in a fault zone and epicenters within a block; the effect being greater with the first than the second. In individual engineering situations, the way in which the seismic stresses affect construction sites is different for those close to fault zones compared to those away from the fault zone, i.e., block locations. A comprehensive analysis of the effects of global stresses and the consequential earth movement in both locations is important when formulating a geo-hazard assessment.

Table 2 Classification of seismic faults

No.	Type	Intersection depth	Historic record (M)	Epicenter intensity (I_E)
1	Sedimentary cover fault (SC)	Sedimentary layers	4–5	6–7
2	Basement fault (BS)	Crystalline basement	5–6	7–8
3	Crustal fault (CR)	To Moho	6–7	8–9
4	Lithosphere fault (LT)	To Asthenosphere	>7	>9

Seismicity of active fault zones

Most strong earthquakes are associated with the movement of faults, often occurring as a reactivation of a pre-existing fracture. Between movements, strain energy is accumulated until such a stress is created that its release causes further movement, i.e., cyclic seismicity. The confining pressures related to deep-seated faults allow the accumulation of higher strain energy and thus produce stronger earthquakes than shallower faults. Zhang (1984) proposed a classification of seismic faults in terms of depth of occurrence (Table 2; Fig. 4), as follows:

1. Sedimentary cover faults (SC): This class of faults develops within the sedimentary cover of the earth's crust. The depth is too shallow for a high level of energy to accumulate, hence movements are more frequent and weaker. A magnitude of Richter scale <4 would be expected.

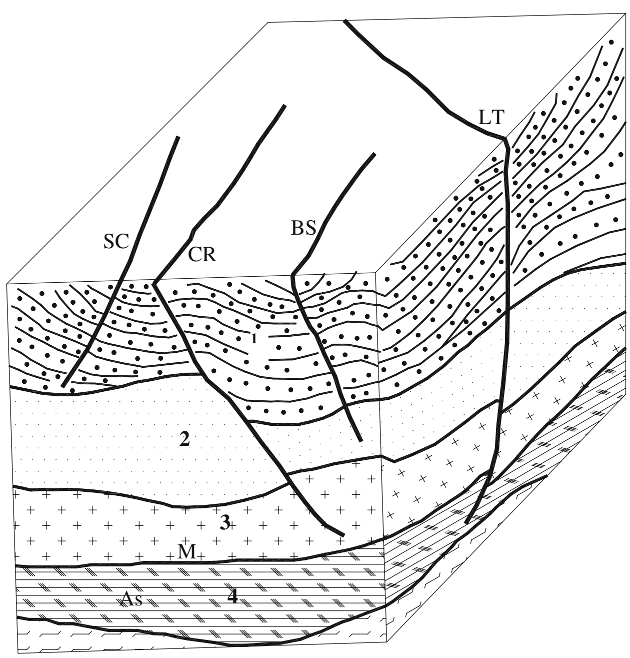

Fig. 4 Classification of seismic faults. *SC* Sedimentary cover faults, *BS* Basement faults, *CR* Crustal faults, *LT* Lithosphere faults, *M* Moho, *As* Asthenosphere, *1* Sedimentary cover, *2* Crystalline basement, *3* Si–Al–Mg sphere, *4* Upper mantle

2. Basement faults (BS): These faults pass through the sedimentary cover into the crystalline basement. Seismic events of $M = 4$–5 are characteristic of this class of faults.
3. Crustal faults (CR): Crustal faults pass through the sedimentary cover and basement to the Moho discontinuity and hence a tremendous energy can be accumulated. Destructive earthquakes are generated from movement of these deep seated faults, with seismic events of $M = 6$–7 and over being typical.
4. Lithosphere faults (LT): Faults in this class are very deep-seated and penetrate into the upper mantle. These faults frequently create the inter-plate boundaries and movement may generate very strong earthquakes with magnitude $M = 7$–8 and over.

The fault zones are of continental scale and comprise crustal and lithosphere faults with boundary fractures while only the sedimentary cover and basement faults are observed in the fault blocks. The magnitude of historic earthquakes associated with the major seismic fault zones in the country is listed in Table 3 and shown in Fig. 3.

Some continental seismic fault zones extend over hundreds to thousands of kilometers and may be up to a 100-km wide. The seismicity varies from place to place hence the further division into sections with potential earthquakes of different magnitudes is important. In addition, as a construction site may not be located directly in the fault zone, it is necessary to study the field of influence when determining the seismic intensity and parameters of ground motion to be taken into account.

Table 4 reports the observed intensity relative to distance from the epicenter for 17 earthquakes; the attenuation relationship is shown in Fig. 5. The following expression can be used to determine the site seismic intensity vs distance from the epicenters.

$$\log D = a - bI \qquad (1)$$

where $a = 3.63$ and $b = 0.23$ for average value, $a = 4.93$ and $b = 0.20$ for upper band, $a = 3.23$ and $b = 0.24$ for lower band and D distance parameter, I intensity

The upper band relates to the low attenuation in fault zones and fractured fault blocks where the hazard spreads across a wide area while the lower band is related to relatively stable fault/blocks where the hazard area is relatively limited.

Table 3 Main strong seismic fault zones

No.	Fault zone	Strike	Length (km)	Displacement rate (mm/a)	Number of earthquakes >M6	Maximum magnitude of historical record (*M*)
1	Taiwan	N30°E	100	12.5	38	8
2	Fujian East	N30°E	300		10	8 (Nanao)
3	Tan-Lu	N30°E	2,500	0.7	12	$8^1/_2$ (Lingyi)
4	Taihangshan	N30°E	700	0.5–1.0	6	North, 8 (Pinggu)
5	Qilianshan	N70°W	1,000		24	7
6	Longmenshan	N30°E	400		13	8 (Wenchuan 2008)
7	Anninghe	N10°E	300	0.47	8	$7^3/_4$ (Xichang)
8	Honghe	N50°W	200	25	5	7 (Honghe)
9	Lujiang	N40°W	200		16	$7^1/_2$
10	Himalaya	N80°W	1,500	32	27	>8
11	Altai	N20°W	200	21	6	8 (Fuyun)
12	North Tianshan	EW	1,000	3.2	11	8
13	Kunglun-Arjin	N70°E	1,500	3.8	15	$7^2/_3$
14	Fenhe	N30°E	600	2.5	9	8 (Zhaocheng, Linfen)
15	Qingling	EW	1,000	2.5	5	8 (Huaxian)
16	South Tianshan	N70°W	500	0.2–0.8	9	$8^1/_4$
17	Xiaojiang	N20°W	400		5	$7^1/_2$ (Dongchuan)
18	West Huashan	N50°W	500	5.5	7	$8^1/_2$ (Guyuan)
19	Helanshan	N30°E	120	0.5	5	8 (Huaxian)
20	Jing-Tang	EW	200	2.0	3	7.8 (Tangshan)
21	Changbaishan	N50°E	700		5	$7^1/_4$ (Mudanjiang)
22	Xuanshuihe	N50°W	400	1–10	10	7.9 (Luhe)

Table 4 Observed distance of intensity contour boundary from epicenter

No.	Epicenter	*M*	I_E	XI	X	IX	VIII	VII	VI
1	Diexi	7.5	X		8	13	27	39	81
2	Linfen	7.5	X		11	28	53	83	
3	Dangxiong	7.5	X		9	27	43	74	96
4	Hongdong	8	X		9	28	53	83	
5	Malasi	8	X		9	18	31	64	120
6	Fuyun	8	X		9	30	67	203	469
7	Quanzhou	8	X			50	72	124	240
8	Sanhe	8	X			18	44	82	170
9	Pinglu	8	X		10	17	31		
10	Songming	8	X		14	20	28	84	178
11	Gulong	8	X			27	95	108	216
12	Tancheng	8	XI		52	99	161	334	474
13	Dangxiong	8	XI		50	95	145	185	
14	Atushi	8	XI		78	137	225		
15	Haiyuan	8	XI	18	48	66	103		
16	Huaxian	8	XI	15	23	45	108	135	
17	Motuo	8.5	XII	60	120	160	207	267	336

M magnitude, I_E epicenter intensity, *XI–VI* intensity of site in a certain distance

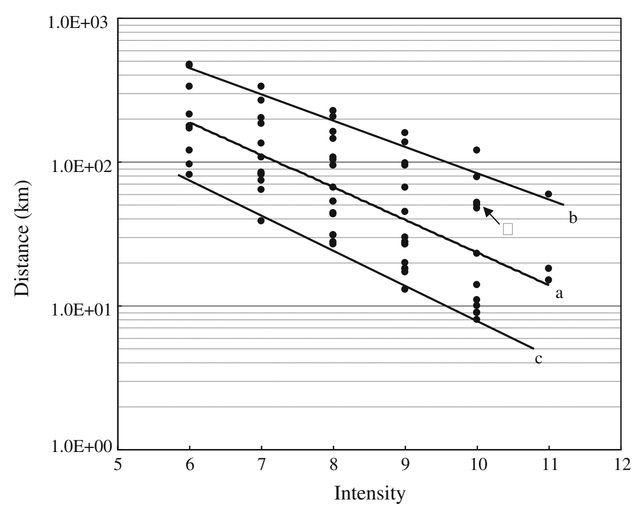

Fig. 5 Observed distance of intensity contour from epicenter. **a** mean band, **b** upper band, **c** lower band, ☐ observed data

Seismicity of Fault-blocks

Taking the constraining boundary conditions and geological characteristics into consideration, the blocks can be divided into four categories (Table 5).

Table 5 Fault-block classification

No.	Type	Boundary condition	Fault type in block	Basic intensity (I_0)
1	Terrain	No strong seismic faults in >300 km	SC	<5
2	Terrain block	No strong seismic faults in 100–300 km	SC, BS	5–6
3	Fault block	Strong seismic faults in <100 km	BS, CR	6–7
4	Fault zone	In strong seismic fault zone	CR, LS	8 and over

(1) Wide terrain: Wide terrain is a vast block unconstrained by boundary fault zones and/or no seismic faults are observed within 300 km. The seismicity is mainly determined by the activity of faults located within the open terrain; the influence of a remote fault zone of high seismicity may be ignored. The seismic intensity is as low as V–VI.
(2) Terrain block: The terrain block is sufficiently large that the influence of boundary seismicity may be similar to that where there are less significant faults. The seismic intensity may reach to VI–VII.
(3) Fault block: When the boundary fault zones are very active such that this is the dominant influence on the block. High intensities of VII–VIII may prevail.
(4) Fault zone: A series of deep-seated, significant faults may form a zone of high seismic intensity, which is controlled by the seismicity of the faults extending to the active crust or lithosphere. The seismic intensity may be high as VII–IX or above.

The (seismic) intensity map of China, issued by the China Seismology Administration in 2002, shows that in the eastern part of China, most terrain and terrain blocks (not seismic fault zones) are of basic intensity V–VI while in western China the intensity may be VI–VII.

Role of ground conditions in seismic geo-hazard

Although seismic intensity is the most important factor, the local ground conditions and pre-existing geo-hazard level also have an influence on the results of a destructive earthquake. Such ground conditions as liquefiable silts, soft plastic clays, karstified rock, coal- and gas-containing layers and ancient river channels may amplify the intensity of the seismic motion and ground failure, creating more damage to the buildings.

Pre-existing geo-hazard level is also important and should be considered. As shown in Fig. 6, high

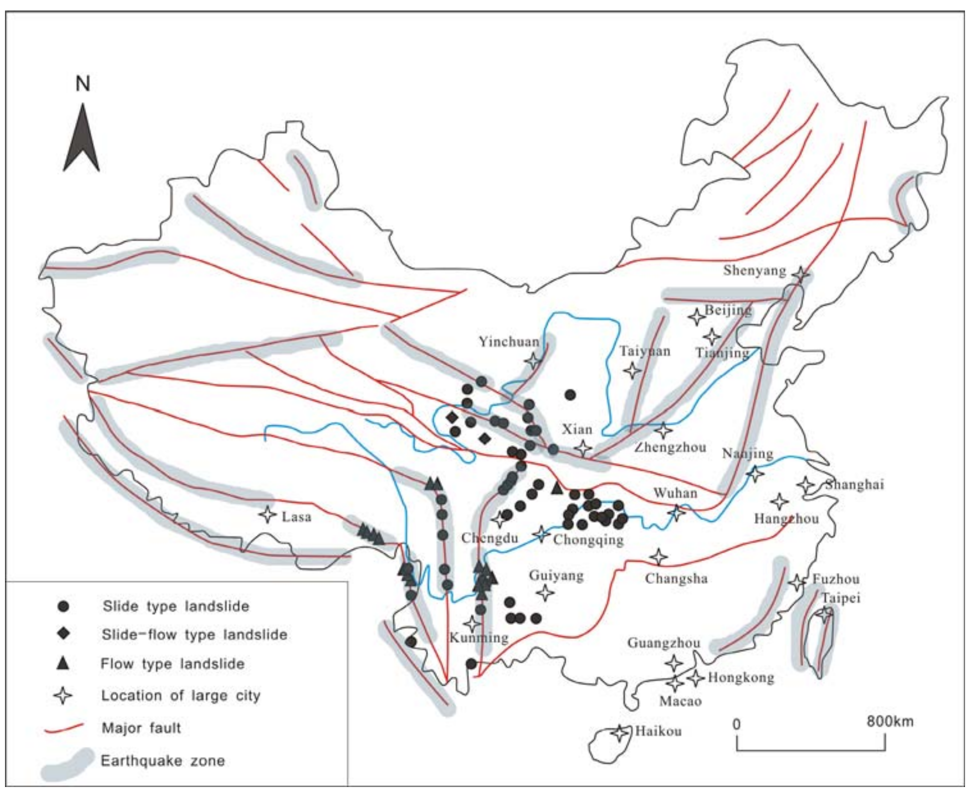

Fig. 6 Location of landslides >10 million m^3 in China with reference to the seismic region

Table 6 Huge landslides triggered by strong earthquakes in 1900～2000 in China

No.	Landslide	Epicenter	Date	Volume × 10^6 m^3	Sliding rock	Magnitude (M)	Epicenter intensity (I_E)
1	Sunjiazhuang	Jingning, Gansu	16.12.1920.	20	Loess	8.5	XI
2	Qilipu	Jingning, Gansu	16.12.1920	20	Loess-bedrock	8.5	XI
3	Huihuichuan	Xiji, Ningxia	6.12.1920	10	Loess	8.5	XI
4	Lijunbao	Haiyuan, Ningxia	26.12.1920	15	Loess-bedrock	8.5	XII
5	Dengshanzhuang	Gulang, Gansu	23.5.1927	10	Loess-bedrock	8	XI
6	Xiaohaizi	Maoxian, Sichuan	25.8.1933	75	Sandstone, slate	7.5	X
7	Xiaoqiao	Maoxian, Sichuan	25.8.1933	46.5	Sandstone, slate	7.5	X
8	Gongpengzi	Maoxian, Sichuan	25.8.1933	30	Sandstone, slate	7.5	X
9	Xiabailazhai	Maoxian, Sichuan	25.8.1933	13.2	Sandstone, schist	7.5	X
10	Dahaizi	Maoxian, Sichuan	25.8.1933	12.76	Sandstone, slate	7.5	X
11	Jiamaqimei	Bomi, Tibet	15.8.1950	10	Marble, granite	8.5	XI
12	Changpingzi I	Ninnang, Yunnan	28.5.1976	71	Basalt	7.5	X
13	Changpingzi III	Ninnang, Yunnan	28.5.1976	67	Limestone, mudstone	7.5	X

concentrations of landslides are found in areas of high seismic intensity and most large landslides happen along seismic faults. Table 6 details 15 landslides of over 10 million m^3 which have occurred since 1900; the large number of seismically triggered landslides recorded associated with the Wenchuan earthquake of May 12, 2008 are not included.

In a seismic fault zone where young uplifted mountain areas, canyons, high steep slopes and old landslides are present, the slopes may be particularly sensitive to the amplified seismic motion compared with the relatively stable terrain in areas of low hills and plains.

Keefer (1984) reports that only a few landsides have been documented in connection with seismic events of magnitude 4 or less (or an intensity below VI). In China only three cases of seismically triggered landslides were recorded associated with events of $M_S = 4.0$–4.1 (Li 2003). This suggests the lower limit for the frequent occurrence of seismic landslides can be defined as magnitude $M_S = 4.0$ and site Intensity $I = \text{VI}$.

Xing and Wang (1999) considered 285 landslides in west China and proposed the following relationship between seismic magnitude (M_S) and distance from epicenter (R) to predict landslides (see Fig. 7, curve 2)

$$M_S = R/(1.775 + 0.118R) \tag{2}$$

For convenience, Eq. 2 can be rewritten in terms of distance as:

$$R = 1.775M_S/(1 - 0.118M_S) \tag{3}$$

The limitation for Eqs. 2 and 3 is $4 < M_S < 8.0$ and the data have a wide spread which implies other factors also influence the occurrence of a landslide, e.g., the relief and geology. It is likely that Eqs. 2 and 3 represent the condition for most fault zones, where the slopes are least stable. For relatively stable terrain blocks, where few landslides had occurred before the earthquake, the seismically induced landslides are likely to be limited to a relatively small distance from the epicenter (Fig. 7, curve 1). The following expression can be accepted.

$$R = 1.275M_S/(1 - 0.108M_S) \tag{4}$$

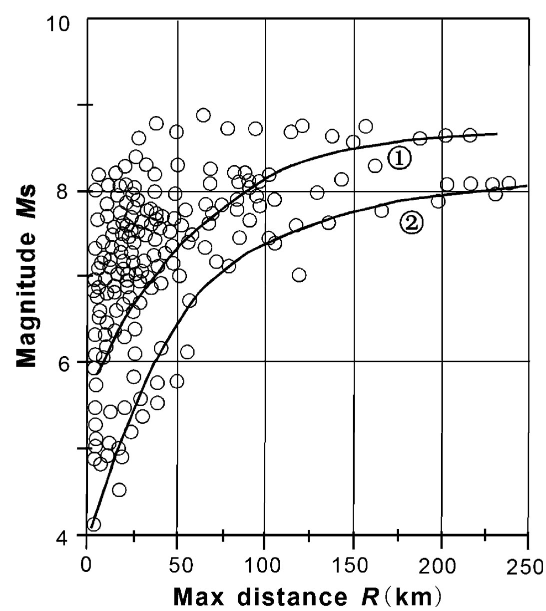

Fig. 7 Magnitude vs distance of landslide from epicenter

Seismic geo-hazard level of engineering sites

The above can be used to determine a method of assessing the most extreme seismic geo-hazard for an engineering site and making recommendations to assist engineers in the planning and design of a project. The seismic intensity basically expresses the seismic loading condition but as noted above, ground conditions and any pre-existing landslide hazard are important factors to be taken into consideration in the assessment. In addition, the vulnerability of the proposed project must be assessed, as different structures/buildings may respond differently to seismic loading. Clearly, hydropower structures present a particularly high risk should there be a collapse.

When undertaking a seismic geo-hazard assessment, the following steps are suggested:

(1) Desk study to summarize the seismology and tectonic features of the engineering site and to identify the seismic faults.
(2) Engineering geological and seismo-geological investigation of the site to characterize the ground conditions and pre-existing geo-hazard level.
(3) Study and classification of seismic faults to define the maximum potential magnitude of an earthquake.
(4) Study and classification of the terrain or block, defining the basic intensity of the block (I_0), taking the local minor faults into account.
(5) Determination of the influence of boundary seismic faults, taking into account the attenuation relationship for the type of block and location of the site. Intensity influence (I_I) can be determined using Eq. 1 based on the likely maximum magnitude of an earthquake on the fault, the related epicenter intensity and the distance of the studied site from the assumed epicenter.
(6) Integration of obtained I_0 and I_I, and determination of general intensity I_G.
(7) Determination of seismic sensitivity of the site in terms of ground conditions and initial geo-hazard level, and determination of seismic vulnerability of the proposed engineering structure to the seismic loading.
(8) Amendment of I_G for ground conditions (Table 7), pre-existing geo-hazard level (Table 8) and vulnerability of the proposed structure (Table 9) to obtain the comprehensive intensity I_S and seismic acceleration parameter g_S.
(9) Assessment of general SGHL from I_S in terms of the site class (I–V).

Table 7 Amendment of SGHL for ground conditions

No.	Ground quality	Rock and soil type	Rock and soil strength	Amendment rate for intensity
1	Excellent	Competent rock	>100 MPa	−0.1
2	Good	Sedimentary rock	30–100 Mpa	−0.05
3	Middle	Weak rock	30–0.5 MPa	0
4	Poor	Sand, clay, karst collapse	<0.5 MPa	+0.1
5	Very poor	Liquefaction, collapse soils		+0.25

Table 8 Amendment of SGHL for normal landslide hazard

No.	Normal landslide level	Landslide frequency	Frequency	Amendment rate for intensity
1	Very low	Very rare landslides	1/100 years	−0.5
2	Low	Occasional landslides	1/10–100/year	−0.25
3	Middle	Few landslides	1/1–10 years	0
4	High	Often landslides	0–10/year	+0.25
5	Very High	Frequent landslides	>10/year	+0.5

Table 9 Amendment of SGHL for building importance

No.	Importance grade	Dam height (m)	Engineered slope height (m)	Surface buildings (floor)	Amendment rate for intensity
1	Local	<20	<30	1–2	−0.5
2	Common	20–50	30–80	3–5	−0.25
3	Middle	50–100	80–200	6–10	0
4	Important	100–200	100–300	10–20	+0.25
5	Very important	>200	>300	>20	+0.5

Table 10 Recommendation for site planning and designing

No.	Item	1	2	3	4	5
1	Seismo-geo-hazard level SGHL	Very low	Low	Middle	High	Very high
2	SGHL class	I	II	III	IV	V
3	Comprehensive intensity (I_S)	<5	5–6	6–7	7–8	>8
4	Recommended seismic acceleration (g_S)		<0.05	0.05–0.1	0.1–0.2	>0.2
5	Ground hazard	Stable ground	Stable ground	Ground deformation	Ground cracking	Ground failure
6	Landslide hazard	Stable slope	Occasional slides	Few slides	Numerous slides	Very dense landslide
7	Dam	No seismic design	No seismic design or seismic design on $g = 0.05$-0.1 for high dams	Seismic design on $g = 0.1$ or $g = 0.1$–0.2 for special case	Seismic design on $g = 0.2$ or $g = 0.2$–0.3 for special case	Seismic design on $g > 0.3$, specially up to 0.5; avoiding seismic fracturing
8	Engineered slope	No seismic design	No seismic design	No seismic design, but static stability factor >1.2	Seismic design on $g = 0.1$–0.2	Seismic design on $g > 0.2$; no major building under slope
9	Civil project	No seismic design	No seismic design	No seismic design, but the structure partly strengthening	Structure strengthening or seismic design on $g = 0.1$–0.2 for high-rise building	Special seismic design on $g > 0.2$; avoiding seismic fracturing

(10) Make engineering geological recommendations in respect of the planning and design of the engineering project at the proposed site (Table 10).

Case studies and discussion

Four case studies of hydropower projects in the south and south-west regions of China are considered: the Three Gorges Project on the Yangtze river, the Ertan hydropower station on the Yalong river in Sichuan and the Xiangjiaba and Xiluodu hydropower stations on the Jinsha river (Table 11). In addition, the seismic behavior of the Zipingpo rock fill dam during the Wenchuan earthquake is discussed.

Three Gorges Project on the Yangtze river

The Three Gorges Project is a large multi-purpose hydraulic project, consisting of a 175-m high concrete gravity dam, a power station with an installed capacity of 18,600 MW, a 5-step two-channel shiplock and other related facilities.

The dam site is located at the center of the Huangling anticline which is composed of Proterozoic Sinian strata and a Pre-Cambrian granite massif. The foundation rock is quite competent; only a few minor faults can be observed and no seismic faults have been found in the dam site.

As shown in Fig. 8a the earthquakes from two seismic fault zones may affect the dam site. The Yiyang-Jiuwanxi fault was associated with an earthquake of $M = 4.9$ at Panjiawen, 90 km from the dam site and other earthquakes of $M = 4$–5 have occurred in the Yuanan fault zone, some 120 km from dam site. The general intensity is evaluated as $I_G = 5.8$. Taking the ground conditions and local landslide hazard into account, the overall intensity may reach $I_S = 6.05$ hence the SGHL should be Low—Class III. As a consequence, the feasibility of constructing a dam at this site was approved, although a higher seismic acceleration parameter of $g_S = 0.15$ was adopted in the design, to ensure the safety of the dam.

Ertan hydropower station on the Yalong river in Sichuan

The Ertan hydropower station on the Yalong River, southern Sichuan, consists of a 245-m high arch dam, a large underground power house with an installed capacity of 3,300 MW and related facilities.

The dam site is composed of syenite and basalt, which are generally quite competent. Only a few minor faults were observed. The Gonghe fault block, where the

Table 11 Seismic geo-hazard level of studied cases

	No.	1	2	3	4
No.	Site	Three Gorges	Ertan	Xiangjiaba	Xiluodu
1	Development stage	Completed	Completed	Under construction	Under construction
2	Dam type	Gravity	Arch	Gravity	Arch
3	Height (m)	180	245	162	278
4	Capacity	18,600 MW	3,300 MW	6,400 MW	12,600 MW
5	Geology	Granite	Basalt, Syenite	Sandstone	Basalt
6	Type of block	Terrain Huanling Massive	Gonghe Fault block	Terrain block	Leipo-yunshen triangular fault block
7	Basic intensity of block (I_0)	5	6.5	6	6.5
8	Boundary fault	CR, Yiyang 90 km M4.9	LS, Anninghe 50 km M6.7	LS, Mabian 49 km M6.7	LS, Mabian 20 km M7
		CR, Yuanan 120 km M4	LS, Huaping 40 km M5.9	BS, Huayinshan 8 km M5.5	SG, Oubian 20 km M
			CR, Ginghe 60 km M5.5		BS, Lianfeng 25 km M
9	Displacement rate mm/year	0.05	0.2–3.0	1.2	1.2
10	Maximum magnitude (M)	4.9 (Panjiawen 90 km) 4.0 (Jiuwanxi 30 km)	6.7 (Yuzha 50 km)	6.7 Mabian 49 km 5.5 Huayinshan 8 km	7.1 Mabian 40 km
11	General intensity (I_G)	5.8	7.1	7.1	7.65
12	Amendment for ground condition	−0.25	−0.25	−0.25	−0.25
13	Amendment for landslide	0	+0.25	0	+0.25
14	Amendment for project grade	+0.5	+0.5	+0.5	+0.5
15	Comprehensive intensity Is (g_S)	6.05 (0.05)	7.6 (0.18)	7.35 (0.16)	8.15 (0.24)
16	SGHL (S_L)	Middle	High	High−	High+, very high
17	SGHL class	III−	IV	IV−	IV+
18	Adopted design seismic acceleration g and engineering measures	0.15 in dynamic computation; anchorage of shiplock slope	0.25 in special seismic design and optimization of arch shape of dam and slope reinforcement	0.22 in dynamic computation; dam abutment reinforcement	0.32 with special seismic design and optimization of arch shape of dam; with abutment slope anchorage

dam site is located, is relative stable, but is a triangular block surrounded by three major seismic faults in the region.

As shown in the Fig. 8b, the Anninghe fault zone with a seismicity of $M = 6$–7 forms the eastern boundary of the block with the Huaping–Dukou fault zone ($M = 5$–6) to the south and the Jinghe–Qinghe fault zone to the northwest. The strongest historical earthquake was the $M = 6.7$ Yuzha event, some 50 km from the dam site. As the earthquakes associated with the other two fault zones are weaker than those related to the Anninghe fault, a general intensity of $I_G = 7.1$ can be accepted based on the Yuzha earthquake.

Taking the ground conditions and local landslide hazard into account, the comprehensive intensity may reach $I_S = 7.6$. As a consequence, the SGHL should be IV, with a g_S of 0.18. A seismic acceleration of $g = 0.25$ was adopted in the design. During the last 18 years of operation the seismic intensity registered at the dam site due to earthquakes in adjacent areas has not exceeded intensity 6.0.

In view of the fact that the dam site is located within a seismic fault block, the engineering measures taken to ensure the safety of the dam included optimization of the arch shape and reinforcement of foundation and abutment slopes.

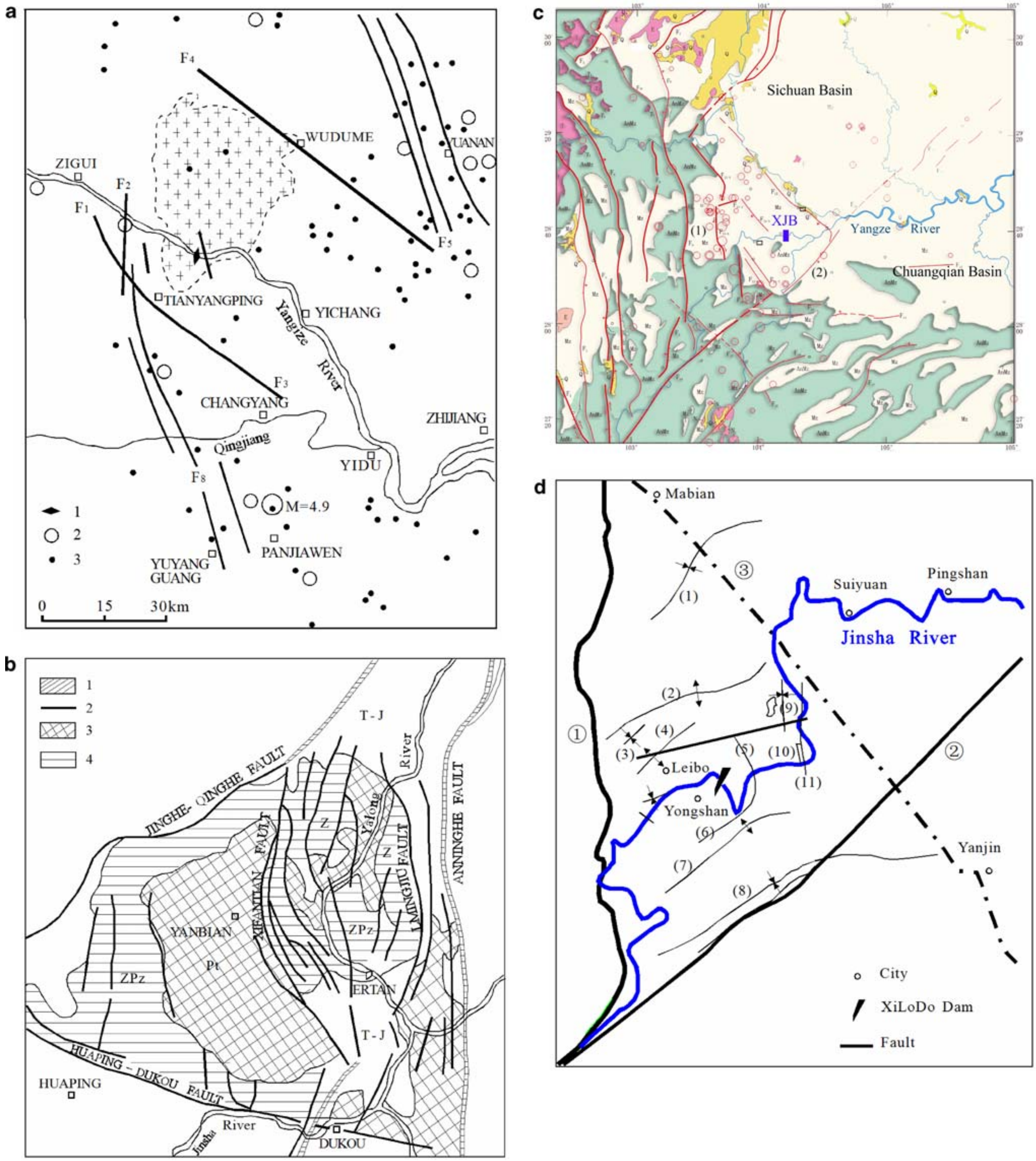

Fig. 8 Seismic geo-hazard level of studied cases. **a** Three Gorges Project (*1* dam site, *2* $M \geq 4$, *3* $M < 4$), **b** Ertan hydropower station (*1* major faults, *2* minor faults, *3* Pre-Cambrian rocks, *4* Palaeozoic rocks), **c** Xiangjiaba hydropower station, **d** Xiluodu hydropower station

Xiangjiaba hydropower station on Jinsha river

The Xiangjiaba hydropower station is the first station of the Jinsha power cascade, upstream of the Yangtze river. This station consists of a 162-m high concrete gravity dam and a power house with an installed capacity of 6,200 MW. The project is currently under construction.

Located on the southern boundary of the Sichuan basin, the dam site is composed of Triassic sandstone with a gentle downstream dip. The rock foundation and abutment slopes are of high quality and stability.

Two seismic fault zones were detected in the region (Fig. 8c). The Mabian fault zone, some 50 km from the site, has experienced earthquakes of $M = 6–7$ while the Huayinshan fault zone with a weaker seismicity ($M = 5.5$) is some 8 km to the south of the site. No seismic faults have been found within 300 km to the north-east. As a consequence, the seismicity of the dam site is determined by the Mabian fault zone, where the influence of the recorded earthquake suggests a general intensity of $I_G = 7.1$.

After the general intensity is amended by taking the ground conditions and project class into consideration, a comprehensive intensity of $I_S = 7.35$ is obtained. A seismic acceleration parameter of $g_S = 0.16$ g was recommended for the planning and design. The SGHL is high to very high at this site and can be classified as IV. In the design computation $g = 0.22$ was accepted.

Xiluodu hydropower stations on the Jinsha river

The Xiluodu hydropower station is the second station of the Jinsha power cascade, upstream of the Yangtze River. The station includes a 278-m high double arch dam and two power houses with a total installed capacity of $2 \times 6{,}300$ MW. The project is currently under construction.

The foundation and abutments of the dam are composed of basalt with some intercalated weak sedimentary layers between the lava flows. The rock is quite competent and intact and the slopes in the dam site are in general stable, with only a few ancient landslides in the reservoir region which are unlikely to affect the safety of the dam.

As shown in Fig. 8d, the fault block where the dam site is located is surrounded by three seismic fault zones within a distance of 20–25 km. To the east of the dam site the Mabian fault zone, with a historical record of seismicity $M = 7.1$, intersects the block. The Oubian and Lianfengdhan fault zones intersect the block on the west and south sides respectively, with seismicities of $M = 4–5$ and $M = 5.0$.

The general intensity of the dam site is dominated by the Mabian fault zone, such that the influencing intensity may reach $I_G = 7.65$. Taking the ground conditions and local landslide hazard into account, the comprehensive intensity may reach $I_S = 8.15$ and a g_S of 0.24 was recommended. The SGHL was considered to be high to very high (IV+) and a seismic acceleration of $g = 0.32$ was adopted for the design computation. In addition, it was recommended that the arch abutments and adjacent slopes should be reinforced with consolidation grouting and pre-stressed anchors.

Seismic behavior of the Zipingpo rock fill dam in the Wenchuan earthquake

The $M_S = 8.0$ Wenchuan earthquake of May 12, 2008, is the strongest to have affected mainland China in the last 50 years. The seismograph recorded peak ground accelerations of $g_h = 0.63$ and $g_v = 0.40$ at Shifang station, some 40 km from the epicenter. Intensities of $I = 7.0$ were recorded over an area of 100×10^4 km^2. Four large dams are located in this area (Fig. 9). Minor damage was recorded but there was no major collapse or local failure.

The most seriously affected was the Zipingpo hydropower station, a multi-purpose project supplying water and power to Chengdu city as well as flood control facilities. The seismic behavior of this plant is of considerable concern, in view of the proximity of Chengdu which could be severely affected by a failure of the Zipingpo dam.

Zipingpo is a 132-m high, concrete plate rock fill dam. In the original design the seismic intensity was evaluated as VII. However, as the dam site is close to the major Longmenshan seismic fault zone, an increase in the intensity was adopted and a seismic acceleration of $g = 0.26$ used in the design computation.

Following the Wenchuan earthquake, the project was immediately examined by a group of experts. As can be seen in Fig. 10a and b, both the dam and the power house appeared generally stable despite the fact that the dam was subjected to a very strong seismic loading. As shown by the seismograms recorded on the top of dam (Fig. 10c), the maximum horizontal acceleration was $g = 0.7$ and the vertical acceleration, $g = 0.5$.

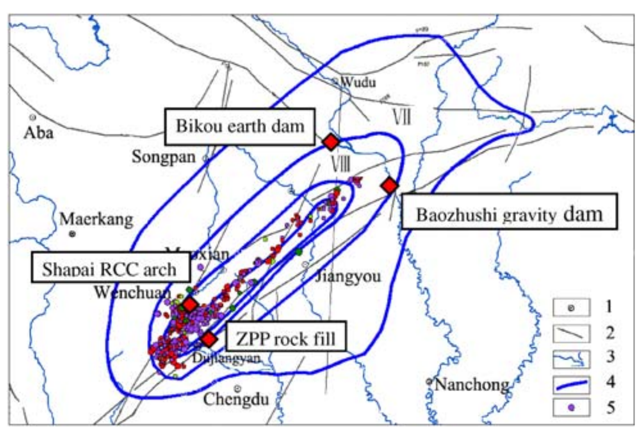

Fig. 9 Location of four dams over 100 m high in the Wenchuan earthquake epicenter area *1* Town, *2* Faults, *3* Rivers, *4* Intensity contour, *5* Epicenter

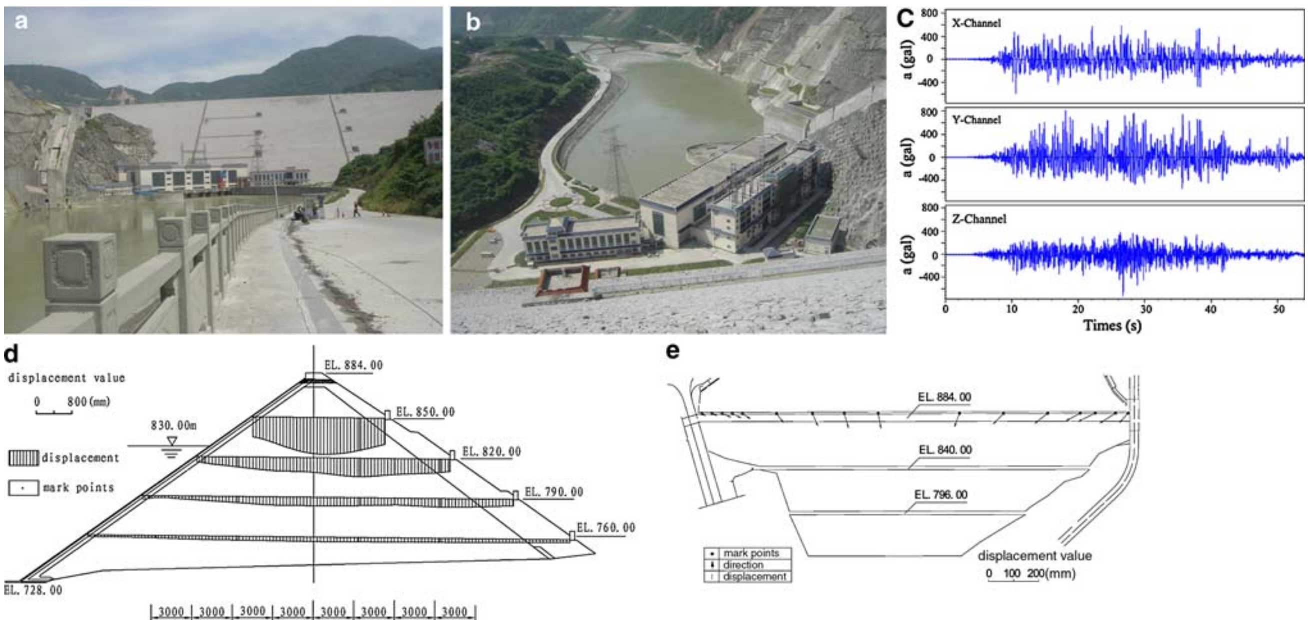

Fig. 10 Seismic behavior of Zipingpo dam in the Wenchuan earthquake. **a** Zipingpo dam, **b** Power house, **c** Seismic record (*a* acceleration), **d** Vertical subsidence of dam top, **e** Horizontal displacement of dam top

Some damage was observed on the surface of the dam, but inspection of the grouting gallery and the low increase in seepage flow (<15 l/s) indicated no serious damage had occurred to the grouting screen or interior of the dam body. Nevertheless, significant distress was observed in the buildings at the top of the dam and the dam itself had obviously been damaged, with open longitudinal cracking at the top and loosening of the masonry stone surface. On the upstream face of the dam one vertical and two horizontal cracks appeared along working joints. The cracks were opened, with slight shear deformation.

Watermarks on the vertical plane of the right abutment indicated 200 mm of surface subsidence while measurements showed the maximum subsidence of the dam reached in 810 mm (Fig. 10d) with horizontal displacements of up to 250 mm (Fig. 10e).

As a consequence, the cut slopes adjacent to the dam abutments, the water intake structure and the outlets of the water tunnels were reinforced by bolting and pre-stressed anchors. The engineered slopes appeared quite stable, with no obvious damage (Fig. 10b).

The repair work lasted almost 3 months and the power station resumed electricity generation and water supply.

The dam is located in an area of seismic intensity 9 (Fig. 9) and the acceleration recorded at the top of the dam reached 0.6 g. While the design acceleration was $g = 0.26$, the dam could be subjected to a seismic overloading of 2.3 without major failure.

Conclusions

1. In addition to normal site assessment, in China the SGHL should also be evaluated, especially for important projects in high seismicity regions.
2. A methodology for SGHL assessment has been developed on the basis of the fault-block concept. A composite terrain model composed of seismic fault zones and fault-block is being established. The model requires the seismicity of the block, the location of the site and the seismicity of relevant boundary fault zones to be taken into consideration. In addition, the ground conditions and initial geo-hazard level should also be taken into account in the assessment.
3. The main steps of the assessment are:

a) Regional investigation for defining the terrain model, including the boundary seismic faults and character of the block at the site location.
b) Determination of basic intensity of the block and the influencing intensity of the faults, taking into account attenuation with distance from the epicenter and the maximum magnitude of historical earthquakes.
c) Comparison of the intensity of the block and the influencing intensity of the faults gives a general intensity (I_G) for the site.
d) The general intensity is modified to take the ground conditions and initial geo-hazard level into account, giving a comprehensive site intensity (I_S) from which the class of SGHL is determined.

e) On the basis of the I_S and SGHL, recommendations are made for the project planning and design, including design seismic acceleration (g_S) and engineering measures.

4. The proposed methodology was considered in relation to four hydropower stations (two completed and two under construction). The results show that the proposed methodology is basically applicable.
5. The Zipingpo dam located in the epicenter area of Wenchuan earthquake, Sichuan, was used to demonstrate the overload capability of a carefully designed dam and highlight the importance of slope reinforcement in ensuring the safety of a dam site.

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