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DAMS SUBJECTED TO EARTHQUAKES - HARMONIZED FEEDBACK DATABASE ACROSS THE GLOBE

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Abstract

The description of the impact of an earthquake on a dam is usually presented in communications published after post-seismic inspection. However, today there is no extensive bibliography of these reports with a worldwide scale. In addition some reports are probably missing, especially when there is no impact observed.

However, this knowledge is essential to better understand the behavior of dams subjected to seismic motions. The huge number of dams and the very limited number of reports describing damage to dams from earthquakes let us assume that dams are robust to this hazard.

This work is a first step to a better description of seismic historical global feedback for dams. The objective is to overlap the worldwide ICOLD database of 30 000 dams with a global ISC-GEM earthquake catalogue of 300 000 earthquake and to select the most significant seismic events observed.

Firstly the "significant" earthquakes are selected with the post-seismic guidance of ICOLD (depending on magnitude and distance between dam and the earthquakes), secondly ground motion prediction equations are used to evaluate the spectral acceleration expected on the dam site for various frequencies.

This "event" database (Fig. 1) can be compared to the post seismic reports published and give us an idea of the completeness of our knowledge of the impact of earthquakes on dams.

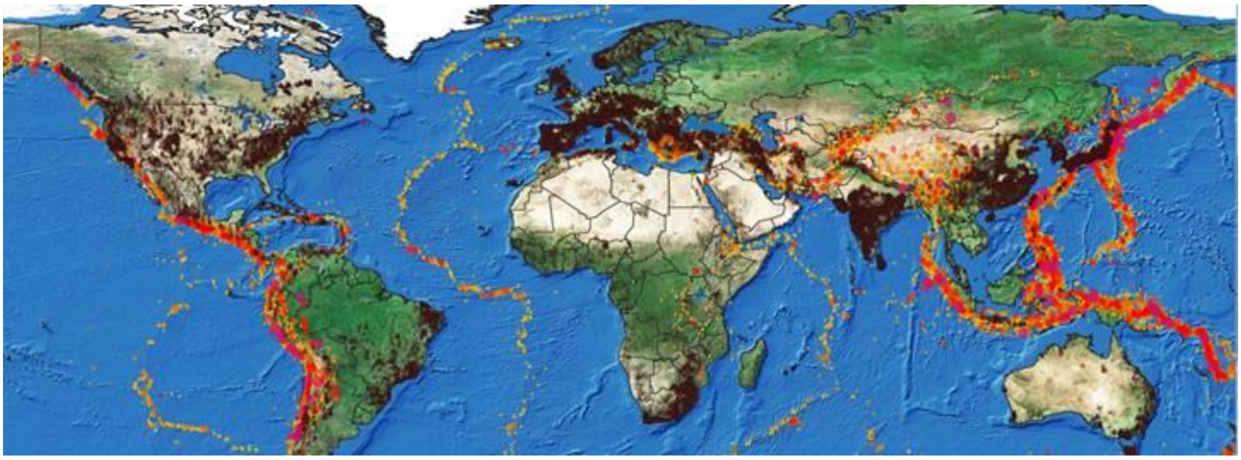

Fig. 1 – global earthquakes since 1900 (>300 000) in orange to red color and dams (>30 000) in brown

Keywords: seismic risk, dams, historical earthquakes, feedback, GMPE

1. Introduction

The objective of this work is to describe the feedback of dams subjected to earthquakes worldwide and to compare it with the post-earthquake surveys.

In order to make this comparison, a series of steps are required and are described in this paper:

- The choice of an earthquake catalogue worldwide
- The choice of a dam catalogue worldwide
- The comparison of the two catalogues based on the ICOLD criterion
- Evaluation of the acceleration at the dam site
- Creation of a catalogue of reported "consequences of earthquakes on dams"

Based on this work, it is possible to give an idea of the completeness of our knowledge of the impact of past earthquakes on dams and the room for improvement which would be needed. Much of historic dam damage analysis is associated with the examples from 1906 San Francisco and 1967 Koyna (0.38g) events, however since there have been over 150 events with some form of dam damage with over 500 entries. It is important to note that for RCC dams subjected to over PHGA 0.3g, so far 5 have had damage, 7 minor damage and 7 have been undamaged ([21]). A selection of event metrics is shown in Table 1 and spatially within Fig. 2.

Table 1 – Significant earthquake events affecting dams and their respective shaking from a selection of 150+ events with dam damage *(D4-5 = major damage/destruction D2-D3 = moderate damage, sliding, major cracking, D1 = minor effects/damage)*

Earthquake, Year (ISO)	D4-5	D2-3	D1	Comments
Kobe 1995 (JPN)	3	6	20	
Chichi 1999 (TWN)	1		2	
Western Tottori 2000 (JPN)			18	
Bhuj 2001 (IND)	11	6	245	Out of 300 dams
Niigata 2004 (JPN)		1	4	
Wenchuan 2008 (CHN)		69	2266	Out of 35601 dams
Maule 2010 (CHL)		5	16	
Tohoku 2011 (JPN)	2	7	39	Out of 341 dams
Bohol 2013 (PHL)			4	
Nepal 2015 (NPL)			14	
Kaikoura 2016 (NZ)			4	

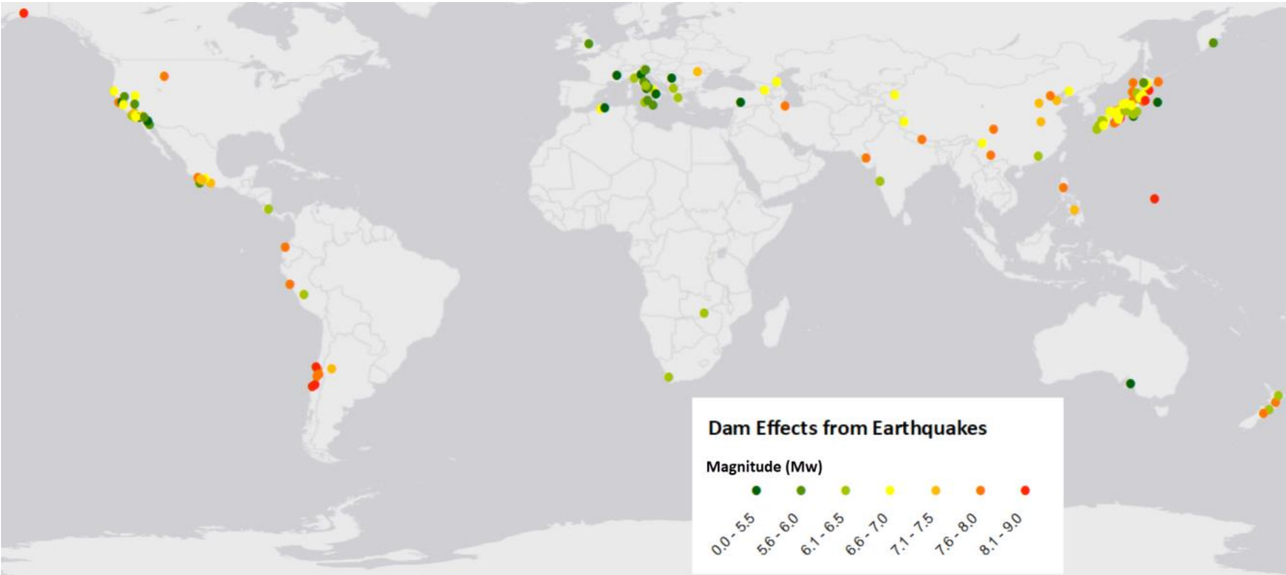

Fig. 2 – Historic Dam Impacts Map from earthquakes

These observations are consistent with the ICOLD bulletin 99 which performs statistics on dam failure modes. This reports demonstrate that the earthquake is clearly not the cause of most of the failures (Fig. 3).

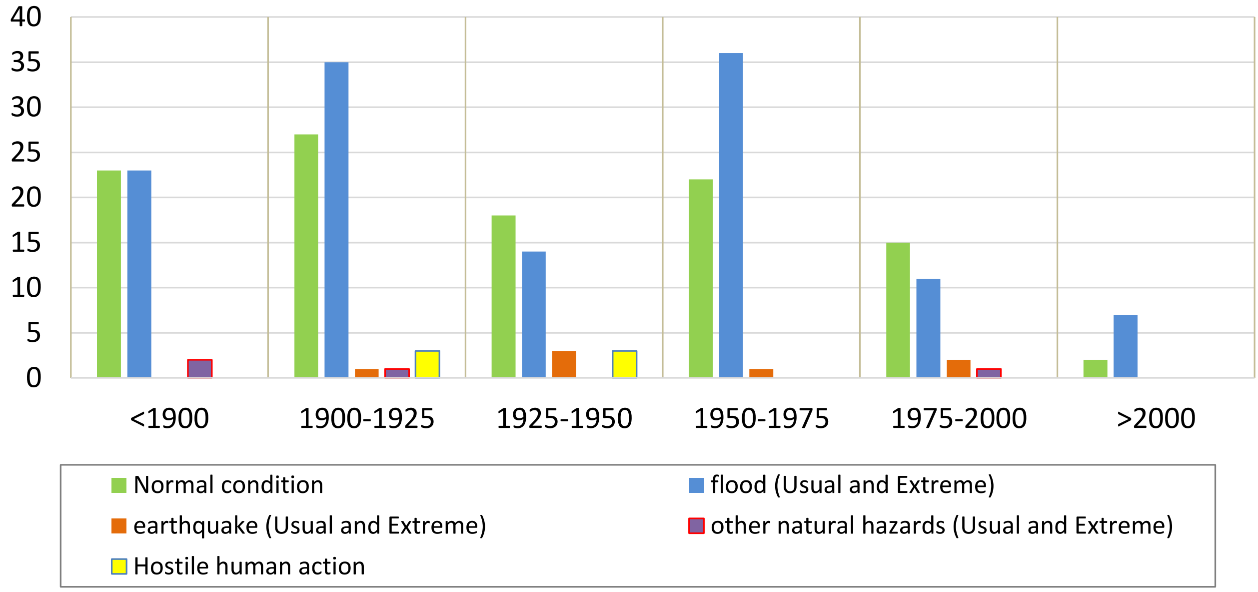

Fig. 3 – Dam failure context – from ICOLD – bulletin 99 update

2. Seismic Hazard on dams

In a first step, the GAR2015 hazard models is observed to identify the dams which have the greater probability to have a seismic feedback. The 2475 year hazard values in terms of Peak Ground Acceleration (PGA) are presented in Fig. 4. The countries that should gather a substantial feedback are visible in orange and red: Japan, California, China, Chile, Turkey, Italy or Iran. These countries fulfill two condition: high seismicity and high number of dams. A stochastic event catalogue over 10,000 years was also used to check the seismicity in order to see that the GAR2015 work was reasonable to employ the cutoff and the selection was refined slightly.

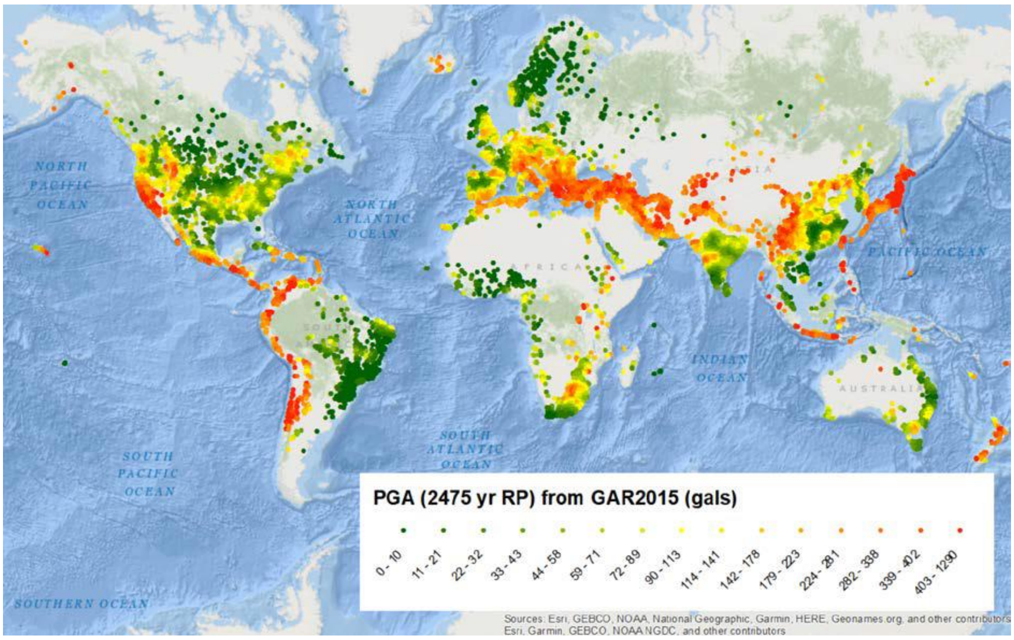

Fig. 4 – Initial Probabilistic global analysis for GAR 2015 Probabilistic hazard

3. Worldwide Earthquake Catalogue

The need for comprehensive and cross-validated post-event databases for underpinning and calibrating models of social and economic disaster losses has been called for by experts in the field for many years (e.g. Mileti 1999; National Research Council, 2006).

The most complete global earthquake catalogue in terms of instrumental earthquake data is the ISC-GEM database from 1904-2014. The ISC-GEM Global Instrumental Earthquake Catalogue (1904-2014) [3] & [4] is the result of a special effort to adapt and substantially extend and improve currently existing bulletin data for large earthquakes (magnitude 5.5 and above) to serve the requirements of the specific user group who assess and model seismic hazard and risk. The catalogue also has a multidisciplinary use in a wide range of other areas such as studies of global seismicity, tectonics, inner structure of the Earth, nuclear test monitoring research, rapid determination of hazard etc.

This global catalogue was also designed to serve as a reference to be used for calibration purposes by those compiling regional seismicity catalogues that contain events of much smaller magnitudes. This way the catalogues prepared by other teams for different regions will contain comparable earthquake locations and magnitude parameters, especially in border regions. The completeness and distribution are shown in Fig. 5 from ISC-GEM.

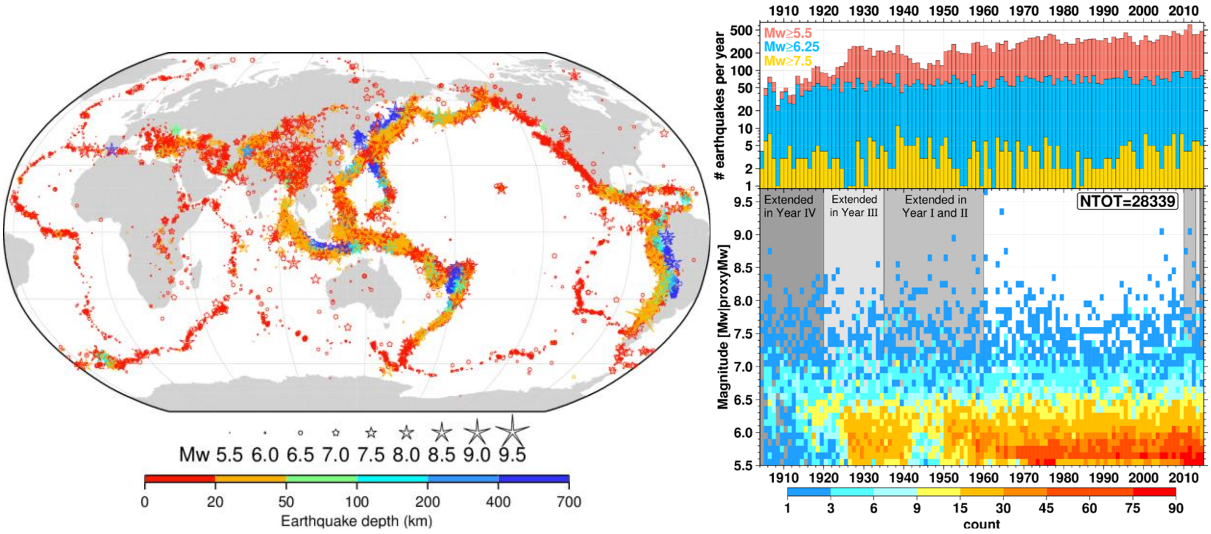

Fig. 5 – ISC-GEM earthquake catalogue global distribution (ISC-GEM, 2018) and completeness.

4. ICOLD dam catalogue

The World Register of Dams is a database including more than 33,000 dams. The Committee of the Register coordinates the data collection within the National Committees. They are included in the database, after validation by the Committee of the Register. The Register, includes only “Large Dams” whose definition is “a dam with a height of 15 meters or greater from lowest foundation to crest or a dam between 5 meters and 15 meters impounding more than 3 million cubic meters”. The catalogue includes a large number of data on dams, but only the information on country, year of completion, latitude and longitude are used in this work.

The World Register is widely recognized as the best data basis on dams worldwide. However, it is still under development as some data are lacking. During this work, a new version of the catalogue was published, updated in 2019. The new data are not included in this work. This update will be taken into account medium term but will not modify the conclusion of this report, because it will only amplify the number of events in our feedback database.

Some other catalogues were analyzed, such as the Global Reservoir and Dam database (GranD) that provides the location and main specifications of large global reservoirs and dams with a storage capacity of more than 0.1 km³ both in point and polygon format for the reservoir. The current contains 6862 records of reservoirs [4]. For this reason, the ICOLD catalogue was selected. In addition individual country archives were also consulted as well as Open Street Map for completeness.

5. Selection criteria

The Guidelines of ICOLD (1988) [6], suggested that the dam operator has to do an inspection of the facilities immediately following a given level of earthquake. This level depends on the magnitude.

For a magnitude greater than 4.0 and an epicentral distance lower than 25 km, a magnitude greater than 5.0 and an epicentral distance lower than 50 km, a magnitude greater than 6.0 and an epicentral distance lower than 80 km, a magnitude greater than 7.0 and an epicentral distance lower than 125 km or a magnitude greater than 8.0 and an epicentral distance lower than 200 km.

These criteria can be derived in a continuous equation, more easy to use in our selection process:

$$k = \frac{5.0 * e^{0.46*M}}{D} \tag{1}$$

with M the magnitude of the earthquake and D the epicentral distance of the dam.

These criteria are consistent with usual ground motion prediction equations, that predict peak ground acceleration (PGA) among other metrics based on magnitude and epicentral distance. Although the GMPE can vary depending on the region, the ICOLD criteria is consistent with a PGA of 0.02-0.03g. This ICOLD criteria is selected because it is widely used and that for such earthquakes, the operator should produce a post-seismic report, based on a post seismic walk down / survey. However, this criterion is not really precise and is linked to a low threshold of earthquake. For this reason, in a second step, a PGA is assessed with GMPEs selected especially for the context of each dam of the ICOLD catalogue.

6. Ground motion prediction equations

A hazard model has been developed over the last few years, combining various global models and tectonic regimes in order to create a modelled 10000-year stochastic event set to be produced for each country globally of which an aggregated 500-year map is shown here in Fig. 6.

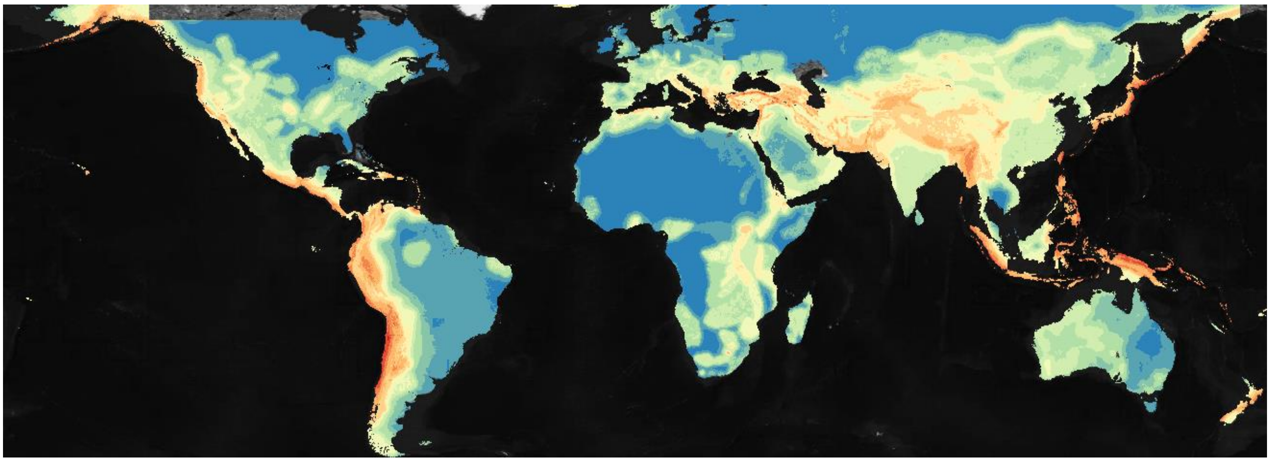

Fig. 6 – Global aggregated hazard map (using the combination of the various hazard models enumerated above) at 500 year return period.

For this model, GMPEs were chosen for each site respective to existing model combinations which have been selected through regional and country models by various authors. The list of this GMPEs cannot be listed in this paper, but have also been used within [20] so the reader is instructed to examine this paper.

These models are used in mean value in order to evaluate an expected peak ground acceleration at the site by running 100 runs of the model for each of the selected earthquakes within the ISC-GEM catalogue respective of the location and type and then compared to the stochastic model. The pseudoacceleration at various frequencies was assessed too but is not included in this paper.

A possible development could be to include an evaluation of the first frequency of the dam, depending on its height and its type. Using generic prediction equation such as Tardieu et al. (1993) [2] for the gravity dams, it is possible to choose the right pseudo acceleration at the right frequency and find an better evaluation of the shear strength at the basis of the dam, more precise than the peak ground acceleration (PGA). For simplification, in this work, the only PGA is presented.

7. Results based on the ICOLD criterion

The crossover of the ISC-GEM earthquake catalogue and the ICOLD dam catalog makes it possible to identify 23,000 seismic events that meet the ICOLD criterion. The ICOLD recommends to take into account the earthquake with magnitudes between 4 and 5.5. Taking these small earthquakes into account multiplies the number of events by an order of magnitude. Because none of these events are identified in the post-seismic reports and the location of these small earthquakes is uncertain (especially their depth), they are excluded from this study.

In Fig. 7, the countries with the most dams subjected to seismic events are reported. The area of the disk is proportional to the number of events: more than half of the global feedback comes from Japan. Indeed the context of Japan is particular: the seismic hazard is high and the number of dam is high too. For this reason Japan is a really good source of feedback for the rest of the countries.

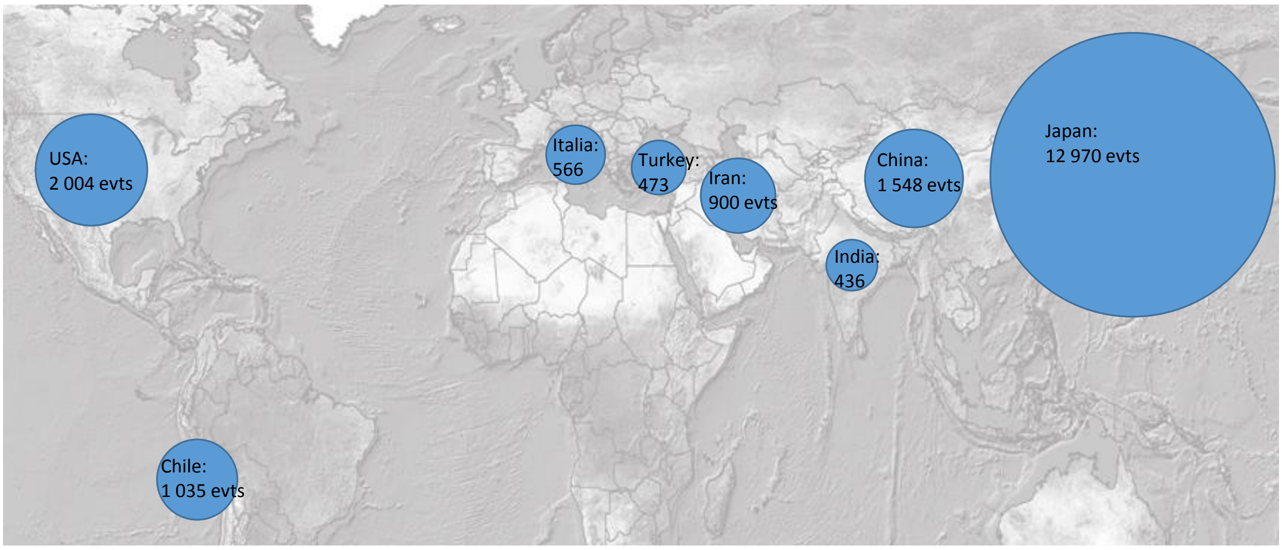

Fig. 7 – Countries with the most dams subjected to seismic events (ICOLD criterion)

Based on the recommendation of ICOLD [6], each of these 23,000 events should be associated to a post-seismic report. Actually, it is impossible to find these reports or to know if they exist. The number of dam owners is huge and the walk down reports are not public (usually they are only send to the safety authority).

For most event we were not able to find any information: the fact that there is no publication is an indication which suggests that the dam has not undergone significant degradation or collapse, but we have no information on potential less significant consequences, such as pressure rise in the foundation, mechanical problems, settlements or concrete cracking.

8. Catalogue of the reported "consequences of earthquakes on dams"

A catalogue of the reported "consequences of earthquakes on dams" was created, based on the available literature in order to evaluate our level of knowledge of the feedback and compare it to the 23,000 events identified. This catalogue gathers even the reports without any impact on the dam (no impact, is an information).

An extensive bibliographic research was carried out to find the publications on a specific earthquake of the existing catalogues published by different countries. The most important sources are listed in the references [1] and [7] to [19].

In Fig. 8, we see the evolution of the event published and on the Fig. 9, the number of seismic events evaluated with the catalogue crossing. Generally, the number of events published is far lower than the real number of events. The factor is more than 10. This gap is much higher if we add the earthquakes with magnitude between 4 and 5.5.

If we look at the shape of the Fig. 8: before the 1960s the number of events published is about 3 per year. This low level can be linked to the number of dams in the word constantly increasing: the same tendency can be observed on Fig. 9. Between 1960 and 2000, the level of seismic events reported increases and fluctuates around 12 per year. After 2000, this level decrease to 3 per year, the same level as before 1960. This evolution compared to the number of events assessed by crossing the catalogue Fig. 9 shows that the decrease of reports for events occurring after 2000 is not a consistent evolution: the number of dams is still increasing and the seismic activity has remained stationary (see Fig. 7). So, this low level of publications after 2000 is linked to a lesser effort of the community to publish seismic feedback on the dams.

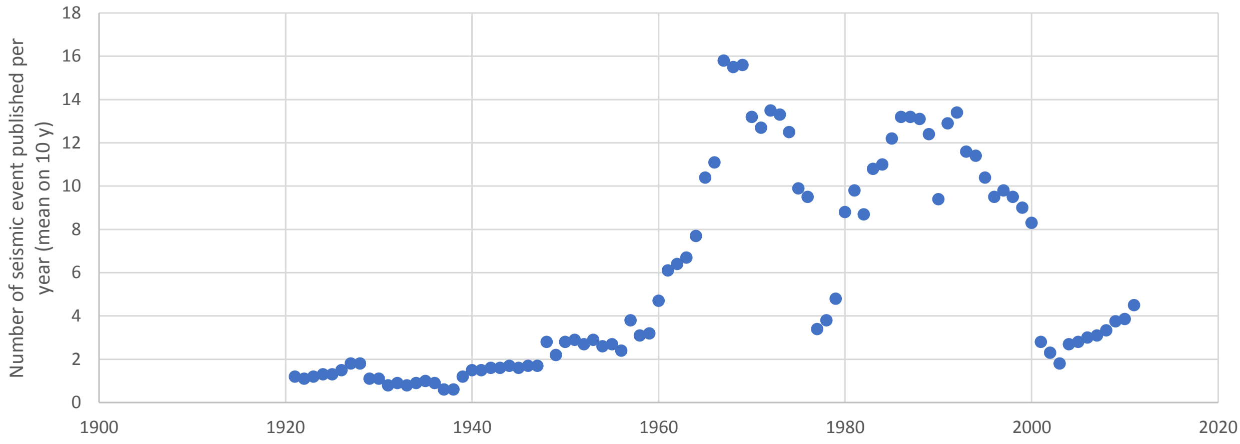

Fig. 8 – Number of seismic events on dams published per year (10-year moving average)

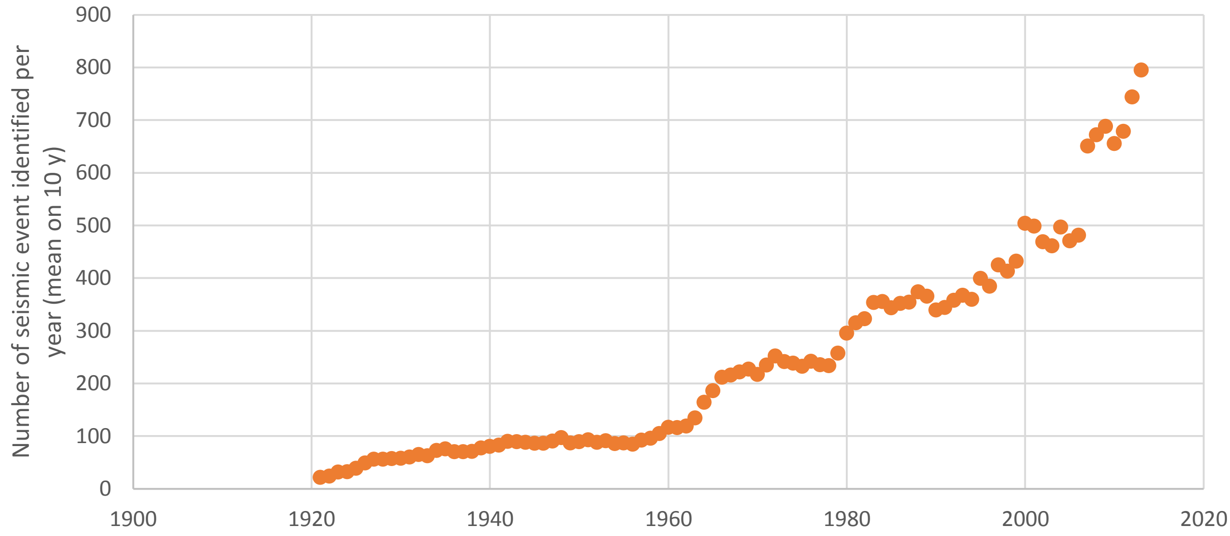

Fig. 9 – Number of seismic events on dams identified in the catalogue comparison (10-year moving average)

9. Results based on the PGA evaluation

The ICOLD criterion is linked to a very low level of shaking (0.02 to 0.03g). Moreover, this level does not include the local specificity of seismicity of each dam. Consequently, a mean evaluation of PGA performed for each dam. The synthesis of the feedback in term of PGA is given in Table 2 and Fig. 10.

Table 2 – Number of events exceeding a level of PGA – without variability – type of dam

		PGA > 0.4g		PGA > 0.2g		PGA > 0.1g		All dams
Concrete	buttress	6	0	321	5	1972	29	243
	barrage		0		3		8	180
	multiple arch		0		0		17	110
	gravity		6		281		1716	4068
	arch		0		32		202	915
Embankement	earth	44	40	450	347	2836	2312	12825
	rock fill		4		103		524	2131

Fig. 10 – Locations of the dams with an evaluated seismic feedback higher than 0.2 g

10. Taking variability into account in the feedback

The variability, due to the source, the path, the site or simply the random variability can lead to a substantial gap with the mean value of ground motion prediction equations (GMPEs). Usually, this overall variability gives a factor about two between the median and the fractiles 15% or 85%. Because we are evaluating extreme events, taking this variability into account will increase the number of significant earthquakes.

A series of 100 sampling of variability for each dam subjected to an earthquake was done in order to evaluate the expected number of events that have really exceeded a PGA threshold. This value is a statistic, on the worldwide dams: it is not possible to come back to a more precise value of the acceleration on a given dam with this study. The Table 3 shows that the effect of variability is non negligible: for example for events exceeding 0.4g, the number is increased with a factor of 10, increasing from 50 to more than 500.

Table 3 – Number of events exceeding a level of PGA – effect of the variability

	PGA > 0.4g	PGA > 0.2g	PGA > 0.1g
Without variability	50	806	5009
With variability	557	2494	7221

The gap between this value and the literature is clear: for example, in reference [1] the expected number of concrete dams shaken by earthquakes with a recorded or estimated peak ground accelerations of 0.20 g or higher is 20. Based on our evaluation, the number of concrete dams shaken by earthquakes with an estimated PGA of 0.2 g is around 321 so 10 times higher than the feedback of the USCOLD in 2000.

Moreover, if the variability is taken into account (see Table 4) the feedback becomes 1018 so 30 times higher than the estimation of [1].

Note: Table 2 and Table 4 show that the seismic feedback of dams is consistent with the proportion of overall dams. For this reason there is more feedback for embankment dams than for concrete dams.

Table 4 – Number of events exceeding a level of PGA – with variability – type of dam

		PGA > 0.4g		PGA > 0.2g		PGA > 0.1g		All dams
Concrete	buttress	200	0	1018	15	2825	45	243
	barrage		3		5		9	180
	multiple arch		0		7		22	110
	gravity		175		881		2481	4068
	arch		22		110		268	915
Embankement	earth	320	248	1386	1117	4103	3337	12825
	rock fill		72		269		766	2131

11. Conclusions

In this paper, the available seismic feedback of dams is evaluated by overlapping an earthquake database (the ISC-GEM) and the global dam catalogue of the ICOLD.

More than 23,000 dams subjected to significant earthquakes are identified. This feedback is translated in a ground motion metric and shows that the available feedback is far higher than that which is published. For example, the number of dams shaken by more than 0.2g should be higher than 2,000.

A catalogue of "consequences of earthquakes on dams" was created based on an extensive bibliographic research. This catalogue highlights that most of the feedback is not published. Moreover, the number of events published shows a decrease since 2000. It seems that the work of publishing seismic walk-downs has been less intense for the past twenty years. This problem has to be addressed because post seismic feedback is essential to better understand the behavior of dams subjected to seismic motions, and it will not be possible to perform good seismic study of dams without a good knowledge of the past behavior and the mode of failure observed (or not) during earthquakes.

The main perspective for this study is to highlight this lack of walk-down reports on dams after earthquakes and motivate dam owners and scientific communities such as ICOLD to initiate actions to gather past feedback (even the feedback of no impact) currently not published.

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