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DAMAGE AND CRACKING OF EMBANKMENT DAMS BY EARTHQUAKE AND THE IMPLICATIONS FOR INTERNAL EROSION AND PIPING (*)

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1. INTRODUCTION

When embankment dams are subject to seismic (earthquake) loads, they may settle, deform laterally and longitudinally, and exhibit longitudinal and transverse cracking. If the reservoir level is high at the time of the earthquake or subsequently before repairs are carried out, the cracking may lead to the initiation of internal erosion. Depending on whether there are adequate filters, zones to discharge leakage flows, and/or there is intervention, this may lead to piping failure of the dam.

Several authors, including Sherard et al (1963), Seed et al (1978), US Committee on Large Dams (1992), Vick (1993), Fong and Bennett (1995), Forster and MacDonald (1998), Swaisgood and Au (1991), and Swaisgood (1995, 1998), have presented useful information on the amount of settlement, and cracking which occurs, often based on observations of performance of dams during earthquake.

(*) *Dégâts et fissuration de barrages en remblai causés par des séismes, et les implications dans les domaines de l'érosion interne et des renards.*

However the data sets used were often limited in number, so the present authors have set out to gather as much case study information as possible from the literature, reports, owners, Internet web sites, and published databases. In all, data for 305 dams, including 95 which reported cracking, was gathered and entered into a database. For these, there was often only limited information available, and the quality of information was often not good. For a further 13 dams, reasonably detailed information on the dam, seismic loadings deformation and cracking was available. Details of the database are given in Pells and Fell (2002).

This data has been analysed to develop damage – seismic intensity relationship and methods for predicting the incidence of longitudinal and transverse cracking for different types of dams.

The information gathered is mostly for dams which did not experience liquefaction, and the discussion in this paper refers to dams which do not experience liquefaction in the embankment or foundation.

2. DAMAGE CLASSIFICATION AND A DAMAGE-SEISMIC INTENSITY RELATIONSHIP

2.1. DAMAGE CLASSIFICATION

Table 1 shows the damage classification system which has been used for this study.

Table 1
Damage classification system

Damage Class		Maximum Longitudinal Crack Width (1) mm	Maximum Relative Crest Settlement (2) %
Number	Description		
0	No or Slight	< 10 mm	<0.03
1	Minor	10 - 30	0.03 - 0.2
2	Moderate	30 - 80	0.2 - 0.5
3	Major	80 - 150	0.5 - 1.5
4	Severe	150 - 500	1.5 - 5
5	Collapse	> 500	> 5

(1) Maximum crack width is taken as the maximum width, in millimetres, of any longitudinal cracking that occurs.

(2) Maximum relative crest settlement is expressed as a percentage of the structural dam height.

With this system, the damage to a dam is described numerically or descriptively, and is determined by choosing the worst case of the above criteria. For example, if a dam records a maximum crack width of 50 mm and a maximum crest settlement of 0.05 %, it is described as 'moderate' damage, class 2. In the case where major discrepancies are found between the crack width and settlement criterion, some averaging is permitted. To use the system it is preferable to have data on both cracking and settlement. However, where data is limited, classification may be done with consideration of only one of these criteria.

The system has been developed taking account of the ideas in ICOLD (1989) and Swaisgood (1995, 1998). It is considered that a damage classification system should include settlement and cracking since settlement alone seldom is likely to cause failure of a dam.

To account for the different quality and amount of data available, it was grouped into data sets as shown in Table 2.

Table 2
Description of damage classification data sets

Data Set	Description
1	Damage classification based on cracking data and given settlement. PGA given or recorded.
2	As for Data Set 1, but PGA calculated.
3	Damage classification based on cracking data and calculated settlement. PGA given or recorded.
4	Damage classification based on given settlement data only. PGA given or recorded.
5	Damage classification based on given settlement data only. PGA calculated.
6	Damage classification based on cracking data only. PGA given.
7	As for Data Set 6, but PGA calculated.
8	Damage based on calculated (Swaisgood) settlement only. PGA given. Alluvial thickness assumed = 0 where not given.
9	Damage based on calculated (Swaisgood) settlement only. This calculation relies on the PGA which was also calculated. Alluvial thickness assumed = 0 where not given.

The database was sorted for each of four dam types:

- Earthfill dams, including zoned earthfill, puddle core, homogeneous earthfill, earthfill with filter or rock toe, and what are described as "rolled" earthfill by some authors
- Hydraulic Fill Dams including fully hydraulic fill and partly hydraulic fill
- Earth and Rockfill Dams – central and sloping upstream core earth and rockfill

- Concrete Face Rockfill Dams.

Each of these data sets was culled so that only data sets that included bedrock Peak Ground Acceleration (PGA), Magnitude and data sufficient to give a damage classification remained.

For PGA, values are sometimes quoted in the source literature. These values sometimes represent readings taken from instrumentation at or near the dam, or are estimations by the author or by seismologists for the dam location. In the absence of such data, the PGA was calculated using the formula by Esteva and Rosenblueth (1969). This formula requires knowledge of the focal depth and epicentral distance. Epicentral distance for each event is often quoted in literature, but where absent, was calculated by using global co-ordinates given for the dam and earthquake epicentre, as provided in the USGS earthquake database. The earthquake magnitude was taken from the USGS database.

2.2. DAMAGE - SEISMIC INTENSITY RELATIONSHIP

Figures 1 and 2 show plots of damage contours versus earthquake magnitude and PGA for earthfill, and earth and rockfill dams. Plots for hydraulic fill and concrete face rockfill dams were developed but are based on limited data; and not reproduced here. They are given in Pells and Fell (2002).

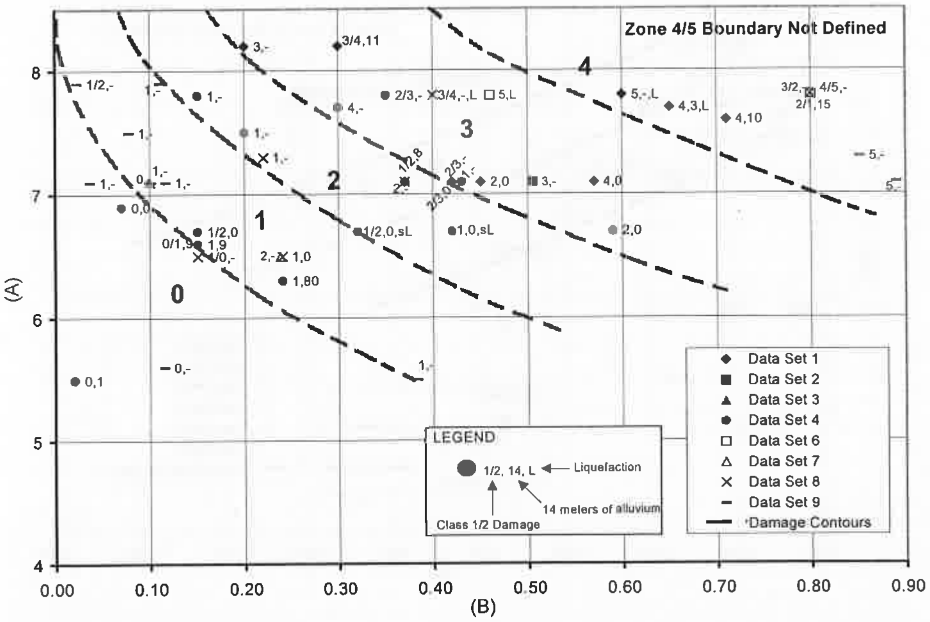

Fig. 1

Earthfill Dams – Contours of damage class versus earthquake magnitude and peak ground acceleration

Barrages en terre – Profils des catégories de dégâts en fonction de la magnitude du tremblement de terre et de l'accélération de pointe du terrain

A. Earthquake Magnitude
B. Foundation Peak Ground Acceleration (as a fraction of acceleration due to gravity)

A. Magnitude du tremblement de terre
B. Accélération de pointe du terrain de fondation (exprimée en fraction de l'accélération due à la pesanteur)

Note: Contours drawn without consideration for cases that had liquefaction

Note: Les profils ont été dessinés sans prendre en considération les cas avec liquéfaction

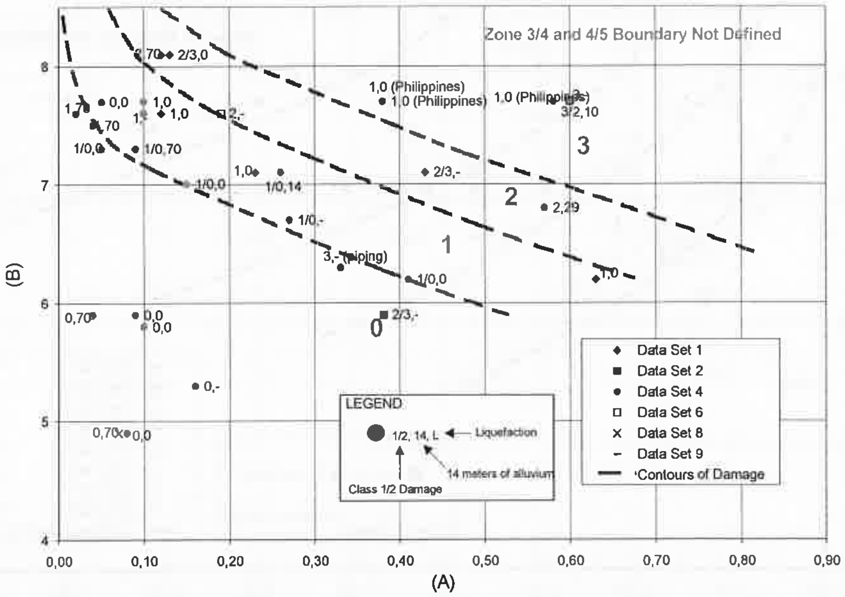

Fig. 2

Earth and Rockfill Dams – Contours of damage class versus earthquake magnitude and peak ground acceleration

Barrages en terre et en enrochement - Profils des catégories de dégâts en fonction de la magnitude du tremblement de terre et de l'accélération de pointe du terrain

A. Earthquake Magnitude	*A. Magnitude du tremblement de terre*
B. Foundation Peak Ground Acceleration (as a fraction of acceleration due to gravity)	*B. Accélération de pointe du terrain de fondation (exprimée en fraction de l'accélération due à la pesanteur)*

Note:

1. Contours drawn without consideration for cases that had liquefaction
2. Boundaries shown assume rockfill is well compacted. For dumped or poorly compacted rockfill use Figure 1 to estimate the damage

Note:

1. *Les profils ont été dessinés sans prendre en considération les cas de liquéfaction*
2. *Les limites indiquées supposent que l'enrochement a été bien compacté. Pour estimer les dégâts dans le cas d'un enrochement déversé ou faiblement compacté, utiliser la Figure 1*

3. SEISMIC INTENSITY AND THE INCIDENCE OF CRACKING

3.1. TYPES AND CAUSES OF CRACKING

There are a number of mechanisms that can cause embankment cracking. Some of these mechanisms are common to those that cause cracking under static loading but some are unique to seismic loading.

Settlement of embankments is almost always reported after earthquake events. In most of the case studies, settlements go hand in hand with horizontal spreading and deformation. Under these movements, strains are set-up in the embankment that manifest as longitudinal, and sometimes transverse cracks.

Differential settlement will set up such strains that, if large enough, will produce transverse cracking. This is a common cause for cracking in embankments from both static and seismic loading. Differential settlements may occur for a number of reasons, but is usually related to changes in geometry or strength and compressibility of material in the embankment or the foundations. This includes: sudden changes in depths of embankment material over the foundation; the existence of highly stressed zones within the embankment; differences in strength and modulus of material, in the embankment and the foundation; difference in degree of compaction of materials used in the embankment. Sherard et al (1963) produced a number of figures explaining the occurrence of cracking from differential settlements.

Fong and Bennett (1995) examined the relationship between settlement and depth of transverse cracking in a number of dams in the western U.S.A. They show a positive correlation between crack depth and settlement with a ratio of crack depth to settlement of 5 or 6.

Cracking can also occur due to overall horizontal displacement and twisting in plan of the dam alignment. This was found to be a relatively common form of earthquake damage, and 26 such cases were recorded in the database. With the embankment crest being displaced in an upstream or downstream direction – often with each end moving a different direction.

Slope failure on a slide surface can be activated by seismic loading. This is often, but not always, associated with loss of embankment and/or foundation strength through liquefaction. The slide surface within the compacted earthfill is likely to dilate, and in effect becomes a "crack". The early stages of formation of a slip surface may result in scarps at the surface that are not dissimilar from longitudinal cracking due to settlement or lateral spreading.

A very significant form of cracking is where cracks occur between two different units eg. the dam, and a wall it abuts. This is known as separation cracking. An example of this was seen in the Austrian dam, where a separation crack over 8 metres deep and up to 500 mm wide at the surface was formed between the left abutment and the embankment. Also at Austrian dam, rocking of the spillway chute under earthquake loading is thought to have caused separation cracks of 7 metres depth and 250 mm width (as well as extensive damage to the spillway. Rodda *et al* (1990) reported that some of the longitudinal cracking at Austrian dam aligned with the location of a line of buried grouting pipes left after construction.

There are seen to be fewer mechanisms that may cause transverse cracking than there are that cause longitudinal cracking. The main reason is that there is a greater degree of freedom for lateral movements in the upstream-downstream direction.

3.2. SEISMIC INTENSITY AND THE INCIDENCE OF LONGITUDINAL AND TRANSVERSE CRACKING

Fig. 3 a and b, and 4 a and b show the incidence of transverse and longitudinal cracking versus seismic intensity and damage class contours for earthfill and earth and rockfill dams.

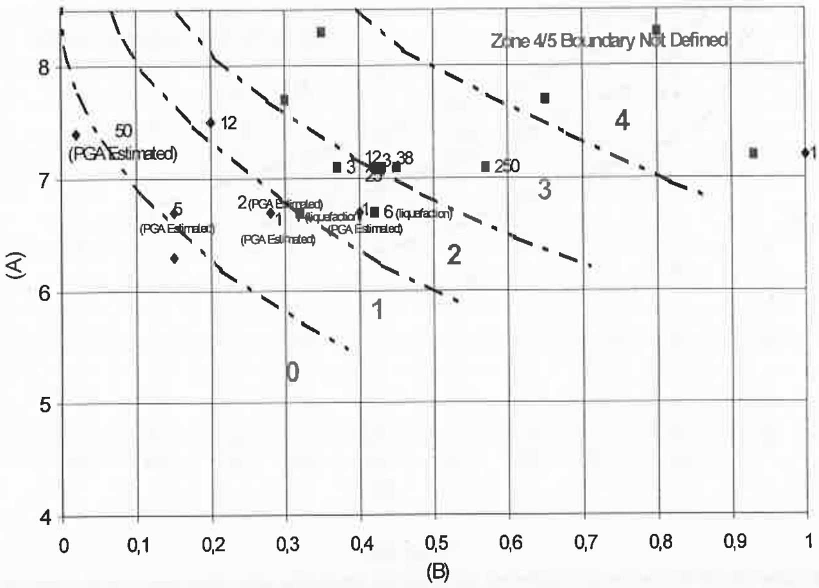

Fig. 3a

Incidence of transverse cracking vs seismic intensity and damage class contours for earthfill dams

Cas de fissuration transversale en fonction de l'intensité sismique et profils des catégories de dégâts pour des barrages en terre

A. Earthquake Magnitude

B. Foundation Peak Ground Acceleration (as a fraction of acceleration due to gravity)

■ Cases recorded only transverse cracking

♦ Cases recorded both longitudinal and transverse cracking

Data labels represent maximum crack width in millimeters and damage class contours

A. *Magnitude du tremblement de terre*

B. *Accélération de pointe du terrain de fondation (exprimée en fraction de l'accélération due à la pesanteur)*

■ *Cas enregistrés pour la fissuration transversale seulement*

♦ *Cas enregistrés pour la fissuration longitudinale et transversale*

Les indications des données représentent la largeur maximale des fissures en millimètres et les profils des catégories de dégâts

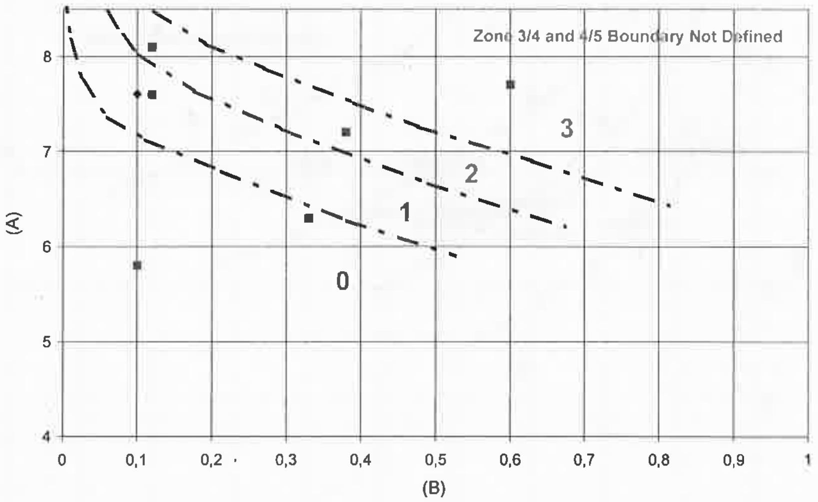

Fig. 3b

Incidence of transverse cracking vs seismic intensity and damage class contours for earth and rockfill dams

Cas de fissuration transversale en fonction de l'intensité sismique et profils des catégories de dégâts pour des barrages en terre et en enrochement

A. Earthquake Magnitude
B. Foundation Peak Ground Acceleration (as a fraction of acceleration due to gravity)

■ Cases recorded only transverse cracking

♦ Cases recorded both longitudinal and transverse cracking

Data labels represent maximum crack width in millimeters and damage class contours

A. *Magnitude du tremblement de terre*
B. *Accélération de pointe du terrain de fondation (exprimée en fraction de l'accélération due à la pesanteur)*

■ *Cas enregistrés pour la fissuration transversale seulement*

♦ *Cas enregistrés pour la fissuration longitudinale et transversale*

Les indications des données représentent la largeur maximale des fissures en millimètres et les profils des catégories de dégâts

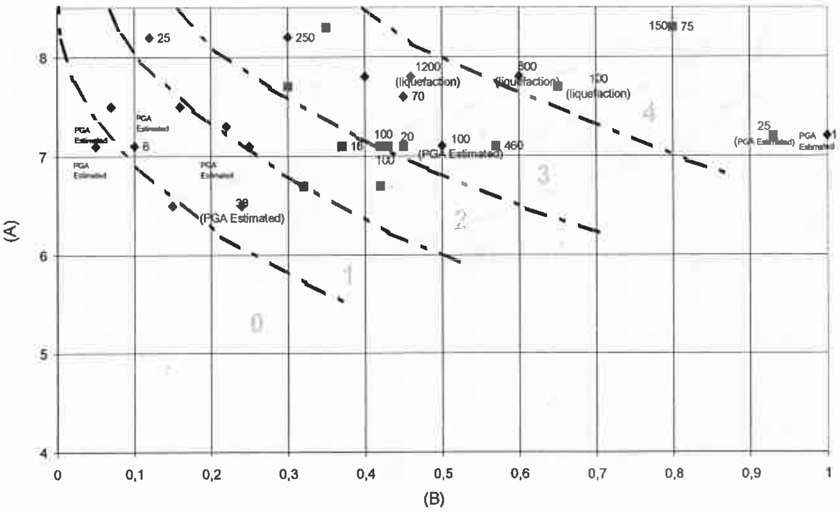

Fig. 4a

Incidence of longitudinal cracking vs seismic intensity and damage class contours for earthfill dams

Cas de fissuration longitudinale en fonction de l'intensité sismique et profils des catégories de dégâts pour des barrages en terre

A. Earthquake Magnitude	*A. Magnitude du tremblement de terre*
B. Foundation Peak Ground Acceleration (as a fraction of acceleration due to gravity)	*B. Accélération de pointe du terrain de fondation (exprimée en fraction de l'accélération due à la pesanteur)*
■ Cases recorded only transverse cracking	■ *Cas enregistrés pour la fissuration transversale seulement*
♦ Cases recorded both longitudinal and transverse cracking	♦ *Cas enregistrés pour la fissuration longitudinale et transversale*
Data labels represent maximum crack width in millimeters and damage class contours	*Les indications des données représentent la largeur maximale des fissures en millimètres et les profils des catégories de dégâts*

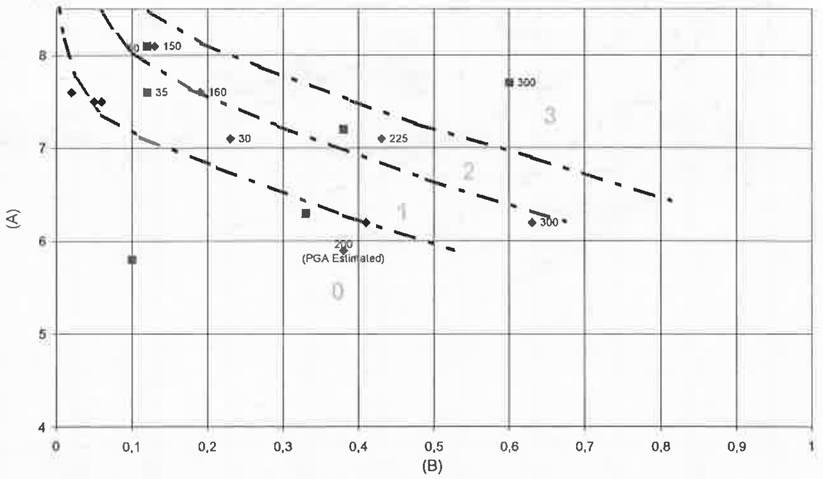

Fig. 4b

Incidence of longitudinal cracking vs seismic intensity and damage class contours for earth and rockfill dams

Cas de fissuration longitudinale en fonction de l'intensité sismique et profils des catégories de dégâts pour des barrages en terre et en enrochement

A. Earthquake Magnitude
B. Foundation Peak Ground Acceleration (as a fraction of acceleration due to gravity)
■ Cases recorded only transverse cracking
♦ Cases recorded both longitudinal and transverse cracking

Data labels represent maximum crack width in millimeters and damage class contours

A. Magnitude du tremblement de terre
B. Accélération de pointe du terrain de fondation (exprimée en fraction de l'accélération due à la pesanteur)
■ *Cas enregistrés pour la fissuration transversale seulement*
♦ *Cas enregistrés pour la fissuration longitudinale et transversale*

Les indications des données représentent la largeur maximale des fissures en millimètres et les profils des catégories de dégâts

Figures 3 and 4 show a trend of increasing transverse and longitudinal crack width with increasing seismic intensity (ie. increasing magnitude and peak ground acceleration).. The trends, although reasonable, are not clearly defined enough to support the drawing of crack-width contours on the Figures. This may be partly due to the variability in measuring and reporting of crack dimensions as discussed by Fong and Bennett (1995), but more likely due to many other variables which are not reported or analysed in this study. The dams which feature both longitudinal and transverse cracking tend to be found at higher seismic intensities (ie. toward the top right corner). It suggests that for high intensity events, both types of cracking can be expected. The data does not provide a clear 'cut-off' of what magnitude and PGA is required to cause cracking.

There is limited data available on the depth of cracking. For transverse cracking it is suggested to use Fong and Bennett (1995), and an understanding of the mechanism causing the cracking to estimate the depth. Figures 3 (a, b) and 4 (a, b), and Fong and Bennett (1995) could be used as a crude guide to crack width. Available data suggests that the ratio of transverse crack depth to crack width at the surface is about 15 to 100, averaging about 40.

4. SUMMARY AND CONCLUSIONS

The study has shown that:

- Earthquakes cause settlement, lateral spreading and cracking of embankment dams. Slope instability may occur but it is not common.
- There are two main types of earthquake induced cracking found in dams -longitudinal cracks and transverse cracks. Longitudinal cracks are more common than transverse cracks, and are mostly in the upper part of the dam, more likely on the upstream face than the downstream.
- There are a number of mechanisms that can lead to formation of either of these types of cracks. Many of these mechanisms are common to both seismic loading and normal operating loading. There are seen to be more mechanisms that may lead to the formation of longitudinal cracks that transverse cracks, largely because lateral displacement is more readily achieved in the upstream-downstream directions.
- A method for predicting the likely extent of “damage” to an embankment dam under seismic loading has been developed. The damage is measured by the relative settlement and the width of longitudinal cracks, and accounts for four different dam types, and the intensity of seismic loading, as measured by the earthquake magnitude and peak ground acceleration.
- For visible longitudinal cracks to occur the dam needs to experience a magnitude 6.5 or greater earthquake, and a peak ground acceleration greater than about 0.15 g for earthfill dams and 0.3 g for earth and rockfill dams or an earthquake magnitude 7.0 or greater, and a PGA of 0.05 g for earthfill and say 0.15 g for earth and rockfill dams. For hydraulic fill dams, visible cracking may occur for magnitude 6 earthquakes, and 0.05 PGA.
- Dams which experience damage of class 2 (relative settlement of 0.2 % to 0.5 % and/or longitudinal cracks 30-80 mm wide) or greater are highly likely to experience transverse cracking. However, transverse cracking has been observed at under M 6.0 to M 6.5 earthquakes, at PGA as low as 0.1 to 0.15 g.
- There is evidence to show that higher seismic loads will result in the formation of larger and deeper cracks, and is more likely to result in

transverse cracking due to the greater differential settlements across the valley.

- At low seismic loading, there is evidence to show that only one type of cracking is likely to develop. This may be either longitudinal (more common) or transverse, depending on factors within the embankment that make it predisposed to a particular form. It is the nature of the embankment, zoning and the foundation geometry and presence of compressible materials and not the seismic loading, that differentiates between which form of cracking develops, and in particular determines whether transverse cracking occurs at low seismic intensities.
- The susceptibility of an embankment to a particular type of crack could not be related to dam type, but a weak relationship has been developed with dam shape (Fong and Bennett, 1995) – dams in steeper valleys tend to show be more susceptible to transverse cracking near the abutments.
- The only way to predict which form of cracking may develop at low seismic loads is to examine the embankment and its foundations in detail, and identify and assess the crack mechanisms that exist. Dams which are susceptible to transverse cracking under static loading will be likely to experience transverse cracking under seismic loads.
- Crack depths may be estimated as described above.
- There is evidence that earthquakes have led to cracking followed by internal erosion, and led to failures of dams. It seems likely that more incidents would have occurred if, in a number of cases, reservoir levels had been higher when the earthquake occurred.

The application of this data to assessing the likelihood of internal erosion and piping is described in Pells and Fell (2002).

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SUMMARY

Embankment dams settle and develop longitudinal and transverse cracks when subject to large earthquakes. A database of case-studies and detailed data for some dams has been analysed to study these phenomena. Methods are presented for estimating the damage (in terms of settlement and the width of longitudinal cracking) and estimating the width and depth of transverse cracks

from the dam type, earthquake magnitude and peak ground accelerations at the dams.

RÉSUMÉ

Les barrages en remblai subissent des tassements et des fissures longitudinales et transversales lorsqu'ils sont soumis à de forts tremblements de terre. Une base de données d'études de cas et des données détaillées pour quelques barrages ont été analysées pour étudier ces phénomènes. Des méthodes sont présentées pour l'estimation des dégâts (en termes de tassement et de largeur des fissures longitudinales), et de la largeur et de la profondeur des fissures transversales, à partir du type de barrage, de la magnitude du séisme et de l'accélération de pointe du sol au site du barrage.