The preparation of an engineering guide to seismic risk to dams
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ABSTRACT

The paper presents the thinking developed for the preparation of "An engineering guide to seismic risk to dams in the UK" (Charles, Abbiss, Gosschalk and Hinks) 1991, as the result of a research contract financed by the Department of the Environment. The derivation of criteria for seismic risk for a country having experienced only moderate seismic activity during recent centuries was based on a study of worldwide experience and practice. The objective was to determine criteria to establish satisfactory levels of safety without unnecessary cost to dams. The understanding and acceptance of the guide by the owners, undertakers and engineers concerned was an important consideration and consultation with such authorities during and after production of a draft guidance document should be and was a significant undertaking.

A code or guide must be prepared in the context of both the purposes which it will serve and how best it can be used in practice.

INTRODUCTION

"An engineering guide to seismic risk to dams in the UK" (The UK guide) was prepared as part of a wider programme of research sponsored by the Department of the Environment to improve the safety of UK dams. In relation to seismic risk, the objectives involved assessment of the seriousness of such risk to UK dams and the preparation of criteria for earthquake safety evaluation of existing dams.

To undertake the work, a research contract was awarded to Sir William Halcrow and Partners Ltd (Halcrow) as a result of competitive technical and financial tendering to prepare a short report on seismic risk to UK concrete and masonry dams. This complemented a draft prepared by the Building...
Figure 1: Sample workflow chart for preparing guide to seismic risk to dams
Research Establishment (BRE) on embankment dams which was subsequently reviewed by Halcrow. BRE integrated the two drafts with advice from Halcrow. The result of this management was that the guidance document was produced under financial and programming constraints considered just sufficient to produce an original document of high quality and stature, the first of its kind in the United Kingdom. A result of the constraints was that the research undertaken was essentially a desk study.

Although the United Kingdom has been a region of relatively low seismic activity and magnitude of events (possibly no more than 5.8 local (Richter) magnitude in the last 290 years), greater magnitudes and the occurrence of peak ground accelerations (PGA) of the order of 0.375 g have been determined as being of a credible probability in the more seismically active parts of the country.

The preparation of the UK guide is thought to provide a good understanding of the problems involved in preparing codes or guides to seismic risk in a much wider international context.

The suggested steps involved are outlined in the workflow chart shown on Figure 1 based on the experience gained from preparation of the UK guide.

PLANNING

In preparing a proposal for preparation of a code or guidance document the three most important steps are probably:

- appreciation of the objectives
- appreciation of the problems to be faced
- selection of a minimum core team and advisers for research and drafting the document

Appreciation of the Objectives

For the UK guide, the objectives were specified by the Department of the Environment as follows:

"To assess the seriousness of seismic risk to UK dams and to prepare criteria for earthquake safety evaluation of existing dams, including embankment, concrete and masonry dams. The end product will be a guidance document for engineers concerned with the safety of UK dams. The report will describe the level of risk which UK dams face from earthquakes and compare this with risks from other hazards such as floods. It will identify the types of dam and ancillary structures most likely to be affected and the mechanisms involved. The state-of-the-art with regard to earthquake safety evaluation will be presented".
It was recognised that the UK guide would be utilised in the context of the Reservoirs Act, 1975\(^2,3,4\) which came fully into effect on 1 April 1986 and established statutory requirements with regard to safety for the design, supervision of construction, surveillance of operation and abandonment of large reservoirs, as defined under the Act and under the responsibilities of undertakers, enforcement authorities and qualified civil engineers. A large proportion of dams under the jurisdiction of the Reservoirs Act are 5m or less in height while the height of the largest (Llyn Brianne) is about 90m.

A precedent for the UK guide already existed, since an engineering guide on floods and reservoir safety had been published by the Institution of Civil Engineers\(^5\) in 1978 and had been put into practice widely by those with responsibilities under the Reservoirs Act. The guide to seismic risk to dams was therefore expected to become a companion document, not with any statutory authority, but by gaining wide acceptance by those with relevant responsibilities.

Thus a clear picture of the use to which the guide would be put was established.

**Appreciation of the problems to be faced**

At the time of preparation of the guide, strong motion records of seismic events in the UK were almost entirely lacking although the coverage of seismic monitoring stations had been extended greatly since the late 1960s. This situation was partly due to the low level of seismic activity experienced in the UK in recent centuries but nevertheless appeared to reflect the situation in many countries suffering a high degree of activity. In recent decades, the science of the mechanisms of earthquakes and their effects has been and still is emerging but is still fraught with uncertainties and unknowns and has to be subject to innumerable hypotheses and simplifications. Faced with a lack of long term data representative of the periods of gradual development of unique stress systems in the earth’s crust, resort has had to be made to compiling knowledge and experience gained from seismic events in other (although hopefully, in some cases similar) tectonic environments world wide. In this situation care has to be taken to make at least qualitative allowance for the possible dependence or interdependence of widely separated events.

The occurrence of earthquakes of local magnitude up to 6.7 where there were no previous reports of significant seismic activity in Australia is well known\(^1,6\). Walter W Hays\(^7\) referred to a situation which well illustrates the long term uncertainty of forecasting probabilities of consistent trends or recurring patterns: The Eastern and Central United States have been relatively quiet this century but events of magnitude up to an estimated 7.5
(New Madrid, on the Mississippi, about 400 miles SSE of Chicago, 1811-1812) and other destructive events occurred there up to the end of the last century.

There is really not enough data on which to predict the future timing of the occurrence of severe events especially in current quiet regions worldwide. In certain settings (eg the Anatolian fault) it may, however, be possible to predict the approximate epicentre of the next earthquake.

Fortunately, Long\textsuperscript{8} and Irving\textsuperscript{9} had separately evaluated the probabilities of exceedance of peak ground accelerations in the UK and, in the absence of strong motion recording of UK earthquakes, Principia Mechanica Ltd\textsuperscript{10,11} had derived applicable response spectra and time histories for vertical and horizontal movements for soft, medium and hard ground conditions. Attenuation relationships had also been proposed by responsible authorities. Therefore it was not considered necessary to re-evaluate probabilities of exceedance of peak ground accelerations, or representation of typical ground motions or algorithms for estimating attenuation. Care was and is needed, however, because Ambraseys\textsuperscript{12} relationship of PGA as a function of magnitude and focal distance can indicate values very different from that of Principia Mechanica\textsuperscript{13}.

Therefore following from the appreciation of the objectives and the problems to be faced, outlined above, it was clear that the guide had to be readily understood and accepted by a variety of users concerned with dams and must facilitate use in practice - it had to be ‘user-friendly’. For example, this led to care in the production of a glossary of terms encountered, applying definitions consistent with international use. It also led to appreciation of the need for a consultation process involving persons and authorities with relevant experience and other likely users.

Selection of Research Team and Authors
The appointment of persons to be given the tasks of producing a guide or code is critical for the value and acceptability of the end product. In particular:

- they need to be eminently authoritative in the fields for which they take responsibility
- they need to be few in number to avoid the ponderous nature of a committee
- unforeseen absences should not unacceptably delay overall progress.

The team involved in preparation of the UK guide comprised two core members from the Building Research Establishment with the necessary background and experience for the work on embankment dams and two core members from Halcrow, one of whom is a member of the All Reservoirs Panel under the Reservoirs Act. The appointment of two core members from
each establishment provided the necessary elements of back-up and fall-back. Professor R T Severn and Dr R M W Musson were the chief external consultants. Professor Severn is internationally eminent in the field of civil engineering and seismic design and research and was chairman of ICOLD’s Committee of Seismic Effects on Dams, responsible for the publication of ICOLD Bulletin 72\(^{(14)}\). Dr Musson has worked as seismologist with the Global Seismology Research Group of the British Geological Survey and is well known for his work on historical seismicity and studies of seismic hazard in the UK and overseas. There were, of course, specialists and colleagues on whom each member of the core team and the external consultants could call in case of need.

CONSULTATIONS

As indicated above, reference to outside authorities was seen as an essential and integral part of the preparation of the guide. This took two forms:

(a) At the outset, three questions were issued to representative authorities, including owners. The questions were worded to ascertain recent practice regarding earthquake loading on dams and to invite views on safety standards and design of dams in the UK for earthquake loading and to request any reasons for applying different standards of seismic risk to concrete tanks as compared to dams.

It may be noted that the questions were few in number to facilitate and elicit a wide response. They were necessary in order to infill gaps in available knowledge.

The results confirmed that it had been unusual for dams in the UK to be designed for pseudo-static accelerations even as great as 0.1g.

(b) At a later stage, a draft of the guide was issued for comment to a representative list of dam owners, inspecting engineers, seismic specialists and other interested parties. 19 replies were received. It is believed that the content of the guide was substantially improved as a result of consideration of the comments received and confidence was gained that the contents would be found widely acceptable on publication.

A principle adopted in preparation of the guide was that the most rational methods practicable should be used in evaluating the safety of dams against realisable combinations of risks of all kinds and that this approach should result in the most cost effective practice. Nevertheless, comments made in discussions after publication have suggested that there are qualified and experienced engineers who feel that there is insufficient justification for the attention to seismic loading which has been recommended. The authors
believe that the return periods of peak ground accelerations for Safety Evaluation Earthquake (SEE) recommended in the guide are realistic and consistent with good international practice and with seismic safety standards applied to nuclear installations and safety standards applied to reservoir safety from floods. It has to be recognised, however, that there are grey areas and a process of inviting and answering comments cannot be expected to lead to complete unanimity.

CLASSIFICATION OF DAMS FOR THE SEISMIC LOADING APPLICABLE

The classification of dams according to risk followed the lines suggested in ICOLD Bulletin 7214. For this purpose the UK was subjectively divided into three zones, A, B, and C, of differing seismicity levels, according to a combination of magnitude and frequency. The return periods and peak ground accelerations recommended for dam categories in each zone are shown in Table 1.

* In many category IV situations it may be considered desirable to use the maximum credible earthquake calculated from a regional geological and seismological survey

# For category I situations seismic safety evaluation is not generally considered to be necessary

The number of dams in the UK falling into each of the four categories is not yet known but a sample of 509 dams, out of a total of about 2450, gives the following distribution:

Table 1: Peak ground accelerations for SEE

<table>
<thead>
<tr>
<th>Dam Category</th>
<th>Return Period</th>
<th>PGA</th>
<th>Zone A</th>
<th>Zone B</th>
<th>Zone C</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV*</td>
<td>30,000</td>
<td></td>
<td>0.375g</td>
<td>0.30g</td>
<td>0.25g</td>
</tr>
<tr>
<td>III</td>
<td>10,000</td>
<td></td>
<td>0.25g</td>
<td>0.20g</td>
<td>0.15g</td>
</tr>
<tr>
<td>II</td>
<td>3,000</td>
<td></td>
<td>0.15g</td>
<td>0.125g</td>
<td>0.10g</td>
</tr>
<tr>
<td>I#</td>
<td>1,000</td>
<td></td>
<td>0.10g</td>
<td>0.075g</td>
<td>0.05g</td>
</tr>
</tbody>
</table>
Table 2: Classification of a sample of UK dams

<table>
<thead>
<tr>
<th>Dam Category</th>
<th>Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>12</td>
<td>2.4</td>
</tr>
<tr>
<td>III</td>
<td>103</td>
<td>20.2</td>
</tr>
<tr>
<td>II</td>
<td>179</td>
<td>35.2</td>
</tr>
<tr>
<td>I</td>
<td>215</td>
<td>42.2</td>
</tr>
<tr>
<td>TOTAL</td>
<td>509</td>
<td>100</td>
</tr>
</tbody>
</table>

The above table relates to dams belonging to some of the major owners who own a relatively high number of large dams. It is therefore likely that, in the whole population, less than 2% will be category IV.

One of the reasons for adopting the ICOLD classification system was to achieve the dual objectives:

(i) To ensure that the largest and most important dams in the country would be assessed in accordance with the best international practice.

and (ii) To avoid calling for sophisticated analysis for smaller dams which might nevertheless be classified as Category A or B according to the definition in "Floods and Reservoir Safety: an engineering guide".

ACCEPTABLE RELIABILITY

The science of seismicity has emerged into focus over the last 60 years or so but it is only since the early 1960s that seismic motion recording instruments have become sufficiently numerous and sensitive to locate the epicentres and focal depths of seismic events with reasonably satisfactory accuracy. There are, however, not only insufficient lengths of record of seismic events to assist in predicting possible magnitudes and frequencies of future events but also insufficient data to define and quantify the mechanism and transmission of damaging effects. A guide to seismic loading must therefore seek to portray orders of magnitude and realistically possible loadings rather than precisely deterministic values.

For the UK guide, vertical and horizontal ground accelerations at the site were adopted as the measure of seismic loading. This was not because ground
acceleration is a parameter sufficient fully to define the effects of an earthquake on a structure, but rather because it has the advantages that:

- it is proportional to the force transmitted
- it has been almost universally adopted in civil engineering as a measure of seismic loading
- it is the parameter for which data have been most generally determined and reported.

Directional time histories reproduce frequencies, duration of shaking and peak ground accelerations at a point and thus provide a complete portrayal of the loading transmitted by the ground. Quantification related to peak or effective values of velocity or displacement or to energy released by the earthquake, must be less directly related to force transmitted and less consistently related to the effects caused.

It is acknowledged, however, that the ground accelerations transmitted by an earthquake are a function of magnitude of earthquake, focal distance and surrounding ground conditions while the seriousness of the effects on a dam are also related to the frequency and duration of the shaking. This points to the need to determine the magnitude and focal distance of the earthquake(s) which is (are) critical for the site in question, as well as the relevant characteristics of the intervening ground. This in turn entails identification of the critical causative fault(s). Whilst in the case of certain major features (eg The Great Glen Fault) this may be relatively straightforward, it is typically more difficult and expensive and indeed is not always feasible. If it cannot conveniently be done the aim has to be to predict realistic orders of magnitude of seismic loading and representative time histories appropriate to the site, rather than site specific values. Provision for the latter approach has been made in the UK guide but the adoption of site specific criteria in some cases was foreseen (see note to Table 1 above).

The difficulties in quantifying earthquake effects are illustrated by attempts to measure the size and effects of an earthquake from the energy released, by introduction of parameters termed "seismic moment" and "moment magnitude" which require evaluation of the area of dislocation of the fault surface, the shear modulus of the medium and the average displacement of slip on the fault surface. It is clear that such measurements can be reliably obtained or estimated only in relatively few cases and therefore the parameters are not of general use in engineering. They have not been used in the UK guide, in which only widely used and accepted parameters were adopted, despite some theoretical limitations.
PERFORMANCE CRITERIA

The UK guide points to the performance criteria presented in ICOLD Bulletin 61\(^{15}\), namely that:

(a) A dam should perform satisfactorily its function without appreciable deterioration during a ‘utilisation scenario’ of conditions expected normally to occur in the life of the structure. The deterioration may include small permanent displacements, limited surface cracking of concrete, some changes in seepage quantities etc.

(b) The dam should not fail catastrophically during a ‘hazard scenario’ of the most unlikely but possible conditions which may be imposed. Such conditions may be permitted to cause extensive distortion and cracking requiring repair but must not endanger safety.

It is not usually considered necessary to consider earthquake loading in combination with design flood or other unusual loadings. The earthquake loadings in a utilisation scenario would be the Design Basis or Operating Basis Earthquakes (DBE or OBE) which are liable to occur on average not more than once during the expected life of the structure (of not less than 100 years).

It should be noted that a definition such as ‘the largest earthquake which could reasonably be expected to be experienced at the site over an arbitrary 100 year span of time’\(^{18}\) was avoided in the guide because what can ‘reasonably be expected’ is a subjective judgement, whereas the definitions of DBE and OBE above represent return periods longer than 143 or, say, 150 years.

The earthquake loadings during a hazard scenario would be the Maximum Credible or Safety Evaluation Earthquakes (MCE or SEE) which would produce the most severe level of ground motion under which the safety of the dam against catastrophic failure should be ensured.

Limiting criteria are proposed in the guide for the performance of both embankment and concrete dams under the SEE.

Permissible deformations

In a pseudostatic analysis of an embankment dam, if with the SEE the factor of safety is found to be less than 1.0, the guide states that it must be demonstrated that deformations will not be large enough to pose any threat of failure of the dam. It is implicit that liquefaction failure of the embankment or its foundations must not occur, that the freeboard must not be lost and that uncontrolled leakage must not develop.
The guide included a review of simplified and empirical deformation relationships. However, a subsequent paper by the authors\(^{(16)}\) has drawn attention to other published work by Ambraseys and Men\(\nu\)\(^{(17)}\) from which can be derived the earthquake induced ground displacements which would be caused by PGAs for a range of probabilities of not being exceeded. The following are examples for a probability of not being exceeded of 1%. The PGAs are given as multipliers which they would be of the maximum PGA which would result in no displacement (i.e., a factory safety of 1.0).

<table>
<thead>
<tr>
<th>PGA as multiplier of PGA for F = 1.0</th>
<th>Resulting maximum displacement (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>1.8</td>
<td>10.0</td>
</tr>
<tr>
<td>2.2</td>
<td>20.0</td>
</tr>
<tr>
<td>3.0</td>
<td>50.0</td>
</tr>
</tbody>
</table>

The implications are that significantly greater ground accelerations than those which would cause zero displacement should be tolerable by embankment dams. While the application of tolerable multipliers of the PGA giving zero displacement is therefore rational in the case of reasonably rigorous dynamic analysis of embankment dams, great care must be taken if this approach is to be applied in pseudostatic analysis due to the simplifications and limitations of pseudostatic methods referred to later, which result in uncertain margins of safety.

The low probability of being exceeded of only 1% is indicated because there must be confidence in a hazard scenario that displacement which could be tolerated without catastrophic failure will not be exceeded. In this context, higher probabilities of being exceeded would not be very meaningful.

It ought to be emphasised that the risk to a dam due to seismicity depends on the stability of the dam under the combination of loading due to all causes applicable at the time.

**DESIGN METHODS**

As a prelude to proposing methods of safety evaluation appropriate for dams in different categories, it was decided that the guide should briefly review the methods of analysis available for design of embankment dams under the headings:
• pseudostatic analysis
• simplified and empirical deformation relationships
• dynamic analysis
• liquefaction analysis

and for concrete and masonry dams under the headings:

• pseudostatic analysis
• standard two-dimensional linear dynamic analysis
• comprehensive two-dimensional linear dynamic analysis
• simplified two-dimensional linear dynamic analysis
• three dimensional linear dynamic analysis
• non-linear analysis.

Each of these approaches has its own merits and conditions of applicability but with improvements in design technology and reduction in its cost, it is proper and to be expected that the more comprehensive and sophisticated methods will be increasingly employed.

It was considered to be important that the guide should draw attention to the limitations of conventional pseudostatic analysis which does not take into account:

• frequency and duration of loading
• effects on loading of the amplification of ground movements within the structure
• inertial effects
• damping effects

In this respect Shieh and Yeh\(^{(18)}\) have drawn a distinction between ‘average peak acceleration’ to be used with dynamic analysis of the dam and the ‘seismic coefficient’ used extensively by engineers with conventional equivalent static methods, which Shieh and Yeh state is an average acceleration for earthquakes with an epicentral distance of at least 100 miles. They remarked that the average peak acceleration can be two to four times greater than the seismic coefficients. If this view were accepted, pseudostatic analyses would not be appropriate for use in the UK unless the causative fault could be identified and were more than 100 miles distant from the site. While Shieh and Yeh’s paper referred to concrete dams, the distinction drawn between average peak acceleration and seismic coefficient relates to location and is apparently equally applicable to any type of dam.

Differing methods of dynamic analysis for concrete dams tend to yield different values of peak tensile stress as has been demonstrated in parametric studies for dams with the cross-section shown in Figure 2. Daniell, Taylor and
Hinks (19) have described such studies which have yielded the curves shown in Figure 3. With each of the methods, the peak tensile stress was reduced when the dynamic modulus of the foundation rock was reduced from 20 GPa to 10 GPa. In the upper part of the dam the pseudostatic method will tend to give lower stresses than the program EAGD-84 by Fenves and Chopra unless the peak ground acceleration is factored up as recommended by Herzog (20). In that case the pseudostatic method may give unrealistically high stresses particularly near the heel of the dam.

The program EAGD-84 takes account of the principal relevant factors including dam-reservoir-foundation interaction, reservoir bed energy absorption, fluid compressibility and radiation damping. Because of this, EAGD-84 was taken as the benchmark method in the guide; further work now in hand at Bristol University will indicate the validity of the assumptions made in the program with respect to radiation damping.

The allowable tensile stress in a concrete dam is not easily determined because cracking is likely to follow the lift joints. Clearly much will depend on the procedures adopted during construction of the dam. Because of the very short duration of seismic loading, it is, however, reasonable to postulate a dynamic tensile strength larger than the static tensile strength. The guide therefore recommends that "the tensile strength at lift surfaces be taken as the minimum dynamic strength determined not exceeding 2.0 MPa". A lower tensile strength will often be considered appropriate.

Finally the guide points out that it will be necessary to exercise engineering judgement to decide whether overstress predicted by a computer program can be accepted in spite of the cracking which it will cause. ICOLD Bulletin 46 (21) states that the Maximum Credible Earthquake should not cause the dam:

(a) to slide on its foundation or at the abutments;
(b) to open at joints or cracks to the extent that uncontrolled leakage takes place; or to fail by local crushing;
(c) blocks or sections of the upper part to be displaced;
(d) spillways and hydraulic controls to be damaged to the extent that dangerous conditions develop.

The short duration of the earthquake and the very transient nature of the peak stresses during that period are significant factors which should influence well informed judgement.
Figure 2: Basic section for typical UK gravity dam

Figure 3: Peak tensile stresses at upstream face for PGA of 0.15G(H) and 0.1G(V) (20 GPa rock modulus)
CONCLUSIONS

The preparation of a guide to seismic risk to dams involves complex considerations which can, however, be dealt with in a simple and logical sequence such as that given in Figure 1.

It is hoped that the work done in preparing the UK guide will facilitate and lessen the work required in preparing future guides for other countries.

RECOMMENDATIONS

It is recommended that after a reasonable period, guides to seismic risk should be reviewed and where necessary, revised.

Guides should not be seen as restricting the discretion of the qualified engineers responsible for dams.

REFERENCES


2 HMSO, Reservoirs Act, 1975


11 Principia Mechanica Ltd " Seismic ground motions for UK design"; Report for BNFL and CEGB, 1981.


