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PROBLEMS IN ASSESSING THE EFFECTS OF EARTHQUAKE ON DAMS

It is difficult to assess future ground motion affecting large structures, failure of which would be catastrophic. The behaviour of mass concrete, and of earth and rockfill in embankments when subjected to earthquake is not well defined. There are few records of the effects of earthquake on dams. Extrapolation from model testing needs verification. The paper presents the problems and proposes further studies.

LA DIFFICULTE D'ESTIMER L'ACTION SISMIQUE SUR LES BARRAGES

Il est difficile d'estimer les mouvements futurs du terrain qui pourraient affecter des ouvrages de grandes dimensions dont la rupture serait catastrophique. Le comportement du béton cyclopéen, et des masses de terre et des enrochements dans des remblais, sous l'action de forces sismiques n'est pas bien défini. Il existe peu d'archives où sont enregistrés les effets des séismes sur des barrages. L'extrapolation des resultats d'essais sur modèles réduits demande à être verifiée. Le présent article presente les problèmes et propose des etudes à poursuivre.

DIE BEURTEILUNG DER AUSWIRKUNG VON ERDBEBEN AUF DÄMME

Die Einwirkung von zukünftigen Erdbewegungen auf grosse Bauwerke, deren Zusammenbruch zu einer Katastrophe führen könnte, kann nur mit Schwierigkeiten eingeschätzt werden. Das Benehmen von Betonmassen, und von Erd- und Steinschüttung in Dämmen wird unter Erdbebenbedingungen nicht wohl erkannt. Es gibt wenige sorgfältig zusammengestellte Erfahrungen der Wirkung auf Talsperren von Erdbeben. Der Übergang in die Praxis von Modelluntersuchungen muss nachgewiesen werden. Im Papier werden die Probleme dargestellt und weitere Untersuchungen vorgeschlagen.

CHAPTER 1 - DETERMINATION OF GROUND MOTION

1.1 Introduction

It is quite clear that it will never be possible to forecast the actual ground motion which will occur at the dam site due to a future major earthquake occurring close to site. It is therefore necessary to choose for design purposes an input of ground motion or force which will have a similar effect on the dam and the associated structures.

1.2 Pseudo-static methods

It has been known for many years that the simple pseudo-static approach using a seismic coefficient (a percentage of 'g', the acceleration of gravity) applied as a horizontal force, does not give a realistic answer when compared with a full dynamic analysis. A compromise solution can be adopted - such as that included in the U.S.S.R. regulations (ref. 1) in which a specified magnification of accelerations with height above ground is taken into account - but even this is not considered adequate for a large important structure for which failure could be catastrophic. A full dynamic analysis and model tests are recommended.

1.3 The problem

A two-fold problem is therefore presented :-

- specification for ground motion which is both realistic and is in a form which can be used in the computations,

- estimation of maximum magnitude (amplitude) of this motion.

1.4 Response spectrum method

It may be mentioned here that the "response spectrum" approach (ref. 2) as proposed for buildings has not yet been proven for large dams.

1.5 Design methods

The method often recommended uses an actual (or synthesized) ground motion based on records from a recording station which is considered from seismological and geological investigation to be similar to the dam site. The record may be scaled to have the maximum amplitude, predominate frequency and duration estimated as appropriate to the site (ref. 3). This requires skilled assessment by the Seismologist, Geologist and Engineer working together. Some dam designers have chosen to assume "white noise" with an estimated spectral density (ref. 4). The methods of computation which are used estimate (as well as the input data will allow) :

- principal stresses in the case of concrete dams,

- stresses and deformations for embankment dams.

In the latter case, some design methods use a finite element approach leading to the examination of critical zones where high shear stress could result in deformation (ref. 5) and others examine the conditions at critical slip surfaces (ref. 4 and 6).

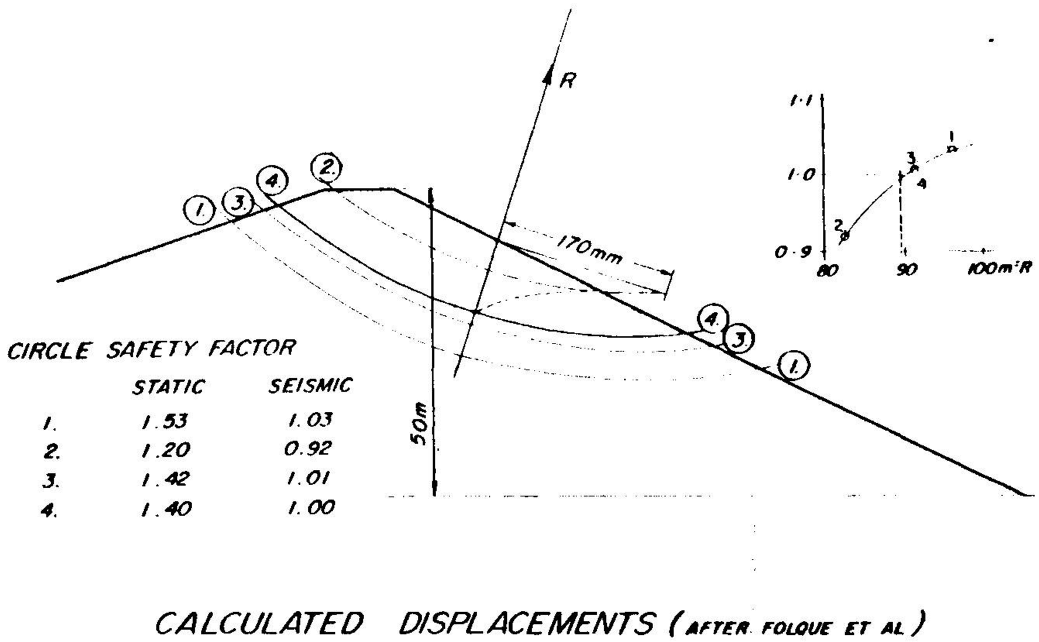

Fig. 1

1.6 Further study and research

It is quite clear that further study and research are necessary before an agreed method of design can be recommended - indeed, it may be necessary to recommend more than one approach. For example, it is possible that different types of failure will become critical for different dams, or even for the same dam. Research work is in progress in many countries which includes the testing of existing dams using man-made vibrations (explosions), and instrumentation to record the effects of actual earthquakes. This will greatly improve our knowledge of dam behaviour within the elastic (or low-level stress) range. Further study of actual dam failures is also necessary related to the seismic events causing the failure and efforts are being made through the International Commission on Large Dams to assemble as much information as possible. For example,

1.6.1 - It is likely that the direction of approach of the ground vibration (horizontal, vertical or intermediate) will have a significant effect. Up to now vertical components of ground motion have usually been either neglected, or included in the design computations in an arbitrary manner; but there is theoretical evidence that the distribution of tensile stresses in an embankment due to vertical vibration is different from and perhaps more likely to be critical than due to horizontal vibration. The effect of vertical vibration on the stability of an unreinforced mass concrete structure is also likely to be significant.

1.6.2 - Examination of the frequency content of natural earthquake at the site could show resonance and the risk of causing resonance in the structure. For example, analysis of the ground motions recorded by instruments at the Lar scheme (embankment dam, tunnels etc.) in Iran has shown natural site resonance at Kalan at a frequency of about 3Hz. Also the frequency content of earthquake depends on geology, and on the distance to, and depth of the event. As another example, Ambraseys has shown that the acceleration response spectrum of the north-south component of motion in the Bucharest earthquake (March 4th, 1977) had an unusually long-period maximum, and structures with corresponding natural periods were worst affected (ref. 7). There is need for a better understanding of the relative effects of focal distances and depths on strong ground motion at sites of structures, both in regard to intensities and durations.

1.6.3 - The mode of failure needs critical examination, and the mathematical model should be able to demonstrate it. For example, earth slopes and escarpments can fail by lurching - i.e. the appearance of vertical cracks running parallel to the contours. Some embankment dams have failed in this manner. The seismic, topographic and soil conditions which lead to this phenomenum require further investigation.

1.7 Seismic Zoning

For the purpose of regional planning in earthquake areas, the procedure of "seismic zoning" is adopted. Maps are prepared which usually divide the territory into zones corresponding to macroseismic intensity related to seismic coefficients tabulated in a code of practise. In recent seismic zoning the "intensity" is further specified on a "probability of occurrence" basis. This does not take into account local geologic or soil conditions, and at the scale of individual developments, micro-seismic zoning of the sites is required. It is a subject for discussion and further consideration as to which parameters should be shown on the microzoning maps, particularly for the sites of dams, where the engineer is interested in amplitude, frequency content and duration of ground motion; also the risk of soil failure with possible landslide, settlement or liquefaction.

1.8 Induced seismicity

Local earthquakes have sometimes occurred after the impounding of large new reservoirs. If "large" is defined as depth of water exceeding 100 m and volume exceeding 10^9 cu. metres, then statistics indicate that this has happened in one out of every 14 such reservoirs. Magnitudes have in some cases exceeded 6 on the Richter scale.

These events may occur close to the dam and at shallow depth. They are therefore potentially dangerous even though the magnitude is not great; and at present there is only limited knowledge about the nature of such ground motions. It is probable that smaller, but important structures associated with the dam may be at greater risk than the dam itself (ref. 8).

CHAPTER 2 - MATERIALS

2.1 Concrete dams

2.1.1 The various gravity types and arch dams of concrete are built without general reinforcement, and the design for static conditions ensures compressive stresses throughout with few exceptions. Variable loading, the effects of temperature changes and gradients, and the variations in moisture content through the concrete often leads to minor cracks, usually at the surface and not very deep.

2.1.2 The addition of rapid and repeated stresses from earthquake can cause new cracks or the propagation of existing cracks. On the other hand, materials are able to withstand higher stresses when the rate of application is high. At the present time the behaviour of concrete under these conditions is not well known.

2.1.3 The overall stability and safety of a structure subjected to earthquake depends on its ability to deform beyond the elastic limit without permanent damage, thus absorbing energy. Again there is little information available about the behaviour of mass concrete under these conditions.

2.2 Slopes and embankments

2.2.1 Natural slopes and embankments are prone to damage by lurching or landslide when subjected to earthquake. Lurching may be a failure in tension or perhaps shear between columns of material vibrating independently. Landslide is failure in shear, and the effect can be much worse if liquefaction occurs.

2.2.2 The properties of materials used for embankment dam construction include the following :-

- Deformation which is not reversible

- Significant volume changes

- Properties which change under wet conditions

- Properties which depend on previous stress history

2.2.3 The deformations therefore depend on the combined static and cyclic conditions of loading, and the laws governing the behaviour of these materials in a three dimensional static stress field when subjected to rapid and repeated stresses, as from earthquake, are not yet fully understood. The representation of soil properties as a visco-elastic continuum is not complete.

2.2.4 Two other particular aspects should be included in further investigations:

- The inertia effect which enables a soft material to resist a sudden blow,

- The failure which occurs at the tension phase of a stress reversal.

CHAPTER 3 - STRUCTURES

3.1 Structure stability

The stability of a structure when subjected to earthquake is largely determined by its ability to withstand stresses beyond the elastic limit. This implies that there will be permanent deformation under severe conditions, as stress beyond the elastic limit leads to some strain which is not recoverable. It has even been suggested that concrete and steel structures should be designed with a factor of safety based on allowable deformation.

3.2 Concrete dams

3.2.1 Concrete dams are a special case in that unreinforced mass concrete is used. The risk of cracking and crack propagation has been referred to above

- but perhaps the greater risk is that movement will take place at construction joints. This is clearly dependant on stress across the joints, and high compression - as for example in a fully loaded arch dam - is going to reduce the risk of movement - either opening or sliding at the joints. It seems therefore that design should particularly take account of vertical dynamic forces combined with horizontal forces, and especially in the case of arch dams (when unloaded) and gravity dams.

3.2.2 Examples of damage to concrete are :-

- Koyna (Maharashtra, India), a concrete gravity dam, which developed horizontal cracks on both upstream and downstream faces at about the level of the change of slope of the downstream face (ref. 1).

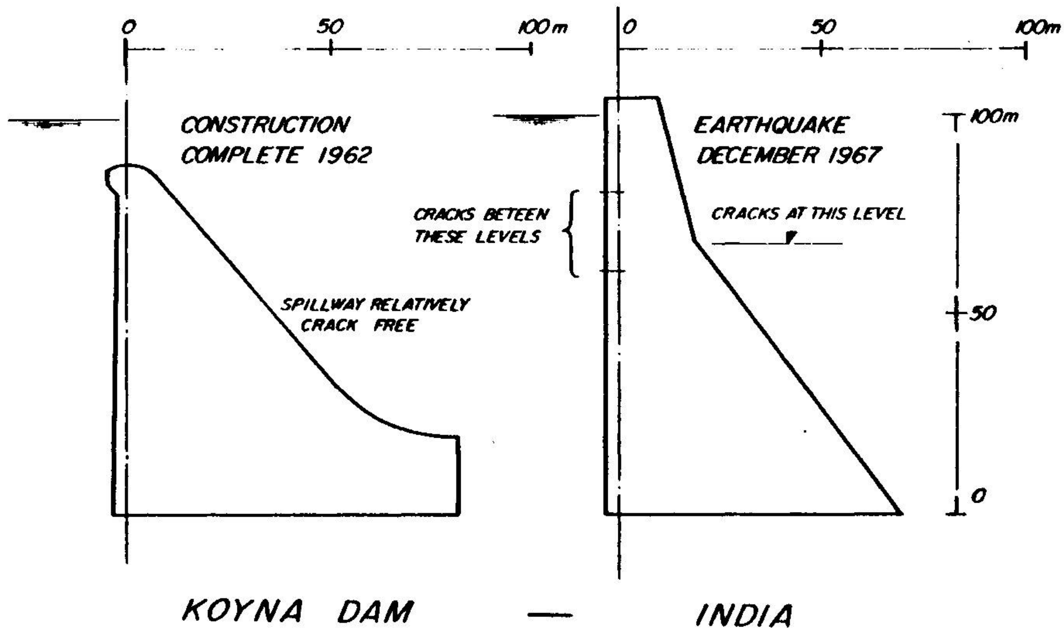

Fig. 2

- Murayama - Upper dam (Japan), an embankment dam, but the parapet wall developed a horizontal crack through it, and some of the concrete facing blocks above water level moved. (ref. 1)

3.3 Embankments

3.3.1 Some embankment dams have been damaged by the development of approximately vertical cracks parallel to the axis of the dam (e.g. Ono dam, Japan, Murayama Lower dam, Japan, and Otani-ike dam, Japan). Other dams have failed by landslide, e.g. Sheffield Dam (U.S.A.) and the Lower San Fernando Dam (U.S.A.) (ref. 1).

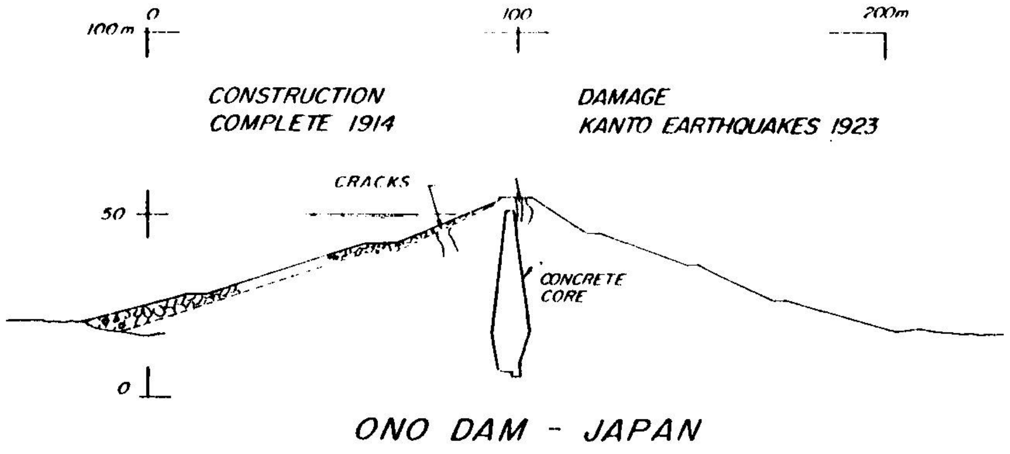

Fig. 3

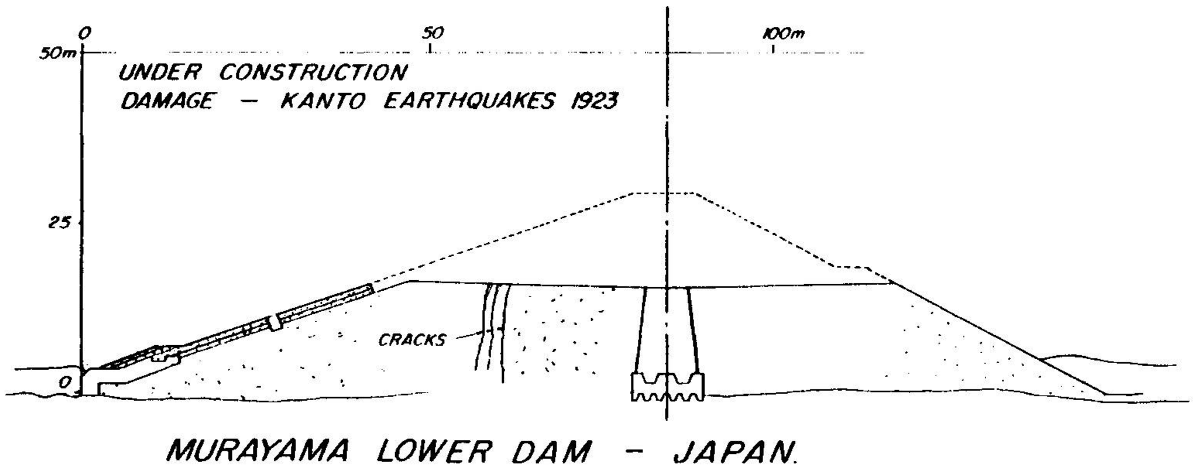

Fig. 4

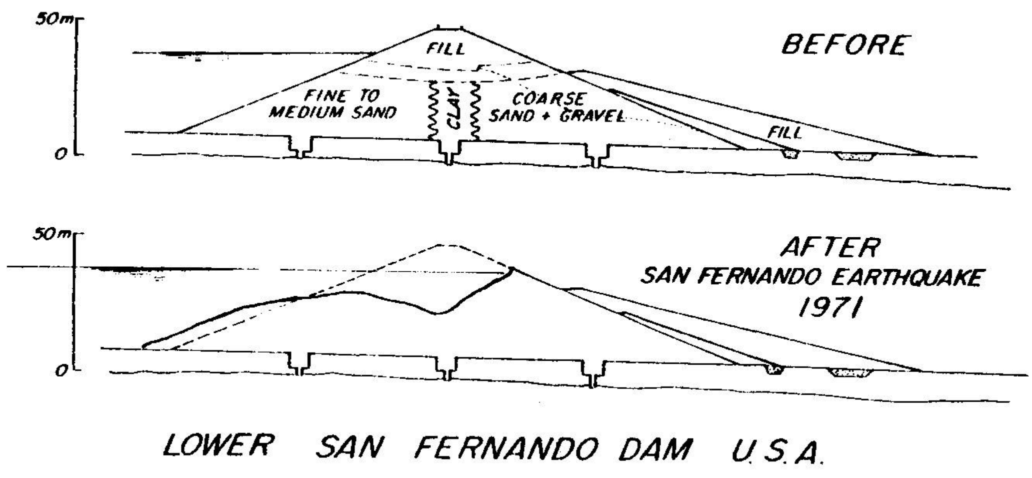

Fig. 5

3.3.2 An analysis of the Sheffield Dam failure has been given by Seed, Lee & Idris (ref. 9) which shows that the assumption that failure would occur on the arc-of-a-circle surface of minimum factor of safety gives a mode of failure very different from that which occurred. A dynamic response analysis using soil strength parameters based on cyclic loading simple shear tests and a finite element analysis, including a study of the liquefaction potential near the base of the embankment, give a mode of failure apparently in accord with the behaviour of the dam during the earthquake. It would, however, be interesting to study the alternative possibility that verticle cracks preceeded the slide failure, as it is recorded that "After examination by several prominent engineers, the conclusion has been reached that the base of the dam had become saturated, and that the shock of the earthquake had opened vertical fissures from base to top; the water rushing through these fissures simply floated the dam out in sections".

3.3.3 It will be noted that the failures referred to have occurred in embankment dams constructed before the days of controlled compaction. Typical modern large dams have cores able to withstand limited tension, and shells which can take almost no tension, but compacted to a friction angle in the forties compared with the low thirties of an older dam. I have no knowledge of any modern embankment dam damaged by earthquake, but this does not mean that damage could not occur, as such dams may not yet have been subjected to strong shaking.

CHAPTER 4 - NEW STUDIES

4.1 Throughout the world engineers and experts in associated disciplines are engaged in study and research on the seismic aspects of dam design. A committee of the International Commission on Large Dams on this subject is supported by working groups in many countries. The time has come for a reappraisal of the "state of the art", and I put forward the following recommendations :-

4.2 Case histories and factual data should be assembled concerning the response of dams to earthquake. The record should include :-

- Seismicity

- Geological conditions

- Materials behaviour

- Structure behaviour.

4.3 Study the stress, strain and deformation of concrete dams when subjected to vertical and horizontal vibration, and the combination of these most detrimental to stability. Relate to case histories and establish optimum shapes and layout of structures; consider the use of post-stressed or other reinforcement where appropriate.

4.4 Consider embankment dams as part of the landscape and examine the effects (stress, strain and deformation) of vibration approaching from below or horizontally, and the combination most detrimental to stability. Relate mode of failure to case histories and establish optimum shapes and layout. Consider use of stainless steel strip or other reinforcement of the embankment where appropriate.

4.5 Continue research into behaviour of materials of construction subjected to rapid and reversal stresses as from earthquake. The risk of liquefaction can be avoided by appropriate specification for the materials and methods of placing embankments, but there may be a risk associated with in-situ materials.

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