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DEVELOPMENTS IN EARTHQUAKE RESISTANT DESIGN OF DAMS

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INTRODUCTION

We have all learnt with great anguish and sorrow the earthquake that shook the Mexico city and the tragedy that followed. From the photographs rhat appeared in the papers, it is seen that some structures, withstood the earthquake while some in the near vicinity crumbled down. This really calls for in depth critical review of the design including detailing that went into these structures and what made the structures fail when the structures nearby were standing. Behaviour of structures in earthquakes have generally shown that structures in which the state of the art design and detailing practices have been followed are less vulnerable and also in many cases withstand severe earthquakes. This is the result of scientific post earthquake investigation carried out by experts leading to continuous review of state of art by the institutions like the School of Earthquake Engineering.

It would be interesting to know how hydraulic structures located near about Mexico city have behaved, as it may have a considerable implication on the designs of hydraulic structures.

SEISMIC DESIGN

Seismic analysis involves the follwing stages :

i) Evaluation of seismic potential of the site
ii) Evaluation of system requirements
iii) Analysis and designing of structure keeping (i) and (ii) as above.

Evaluation of seismic potential of the site.

This calls for engineering juegement and assessment of tectonic conditions prevailing at the project site which is based upon history of post earthquakes and assessment of tectonic features of the site. After the Konya earthquake the seismic zoning map of India has been revised with the result the entire country is considered prone to earthquake and the country has been divided into five seismic zones. After the Konya earthquake

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Government of India has consituted a standing committee under the Chairmanship of Member (D & R), CWC to recommend Design Seismic Co-efficient to River Valley Projects. On this Committee GSI, IMD, School of Earthquake Engineering, Roorkee and NGRI, Hyderabad are represanted. The data on dams are received by the Committhe and seismic parameters are recommended for design of dams. Most of the past designs are based on IS 1893-1975 (revision thereatter). In respect of some of the new projects taken up now, micro-seismic Instruments have been installed even at the investigation stage to asses the seismic status/anticipated movements along faults etc. Such instrumentation has helped in identifying probable epicentres in the area of project. This approach has been adopted in recent projects including Sardar Sarovar, Narmadasagar and Edamalayar. With the exploitation of favourable sites in the various plains, we now have to go in necessarily for reservoirs in the Himalayan and North Eastern Regions where the seismic activity and their occurrences are far greater than in other parts of the country. Designing structures taking one seismic parameter would make these structures very costly and thus calls for evaluation of seismic potential on a two tier basis.

— Design basis earthquake (DBE)
— Maximum credible earthquake (MCE).

The desien basis earthquake is defined [1] as the earthquake capable of producing the largest intertia forces on the dam expected to occur during its economic life. The DBE is primarily determined from historical magnitude versus fréquency of occurrence relationships. The recurrence interval for the DBE is normally defined as once in 100 years.

The dam is required to safely withstand the loads due to the DBE although some repairable damage is acceptable for this loading. Those systems and components important must remain operatable during and after the ground motions associated with the DBE.

The maximum credible earthquake[1] is defind as the earthquake that would cause the most severe vibratory ground motion capable of being produced at the site under the currently known tectonic framework. It is a rational and belierable event which can be supported by all known geologic and seismimologic data. The MCE is determined by judgement based on the maximum earthquake that a tectonic region can produce, considering the evidence of past movement and the recorded seismic history of the area.

The dam is to be checked to ensure that it can withstand the loads resulting from the MCE without any sudden or uncontrolled release of te reservoir even though damage may occur. The structures, systems and components of the project critical to retention or controlled release of the reservoir are required to function during and after the MCE.

2.02 System Requirements

System requirements define the conditions that a syetem is expected to satisfy in accordance with its intended use. For structural system these requirements are grouped as follows :

(i) Safety; and

(ii) Serviceability.

2.03 Safety requirements for structural members assumed to contribute to earthquake resistance should be consistent with the intended safety of the structural system, and should cover a possible influence of cumulative damage and degradation of mechanical properties.

2.04 Structural elements assumed not to contribute to earthquake resistance should maintain, with an adequate reliability, their integrity during and after the occurrence of seismic actions, and should not adversely affect the behaviour of the structure and other structural elements.

3 00 ANALYSES AND DESIGN OF STRUCTURES

3.01 The selection of appropriate procedurs for analysis and designs would depend upon the following points :

(1) Classification of structure :

(2) Basic dimension of the sturucture with proper reference to seismic potential, and

(3) The acceptance criteria evolved by the country in question.

Classification of Structure :

By and large in India. dams are masonry/concrete gravity structures (except the Idukki dam in Kerala) or earth and earth-core rockfill dams. In the past and even now we have been using the pseudo-static method for design of the structures. However, as already brought out by me earlier, we are being called upon to design dams in highly complex geological project sites riddled with complex tectonic features. This calls for a need to economise in design consistent with safety requirement of the system.

The methods for analysis and design of dams are discussed further with special reference to the four types mentioned above.

4.00 CONCRETE AND MASONRY DAMS

4.01 Currently in India the procedure adopted for earthquake resistance design is based on the conventional pseudo-static method [a] and in case seismic zones of high intensity and/or high dams over 50 to 60m. further detailed dynamic analysis by using Finite Element method or by simplified method has now come into vogue. For the dynamic analysis for the behaviour of the structure the method suggested by Dr. A. K. Chopra[a] wherein stresses are calculated approximataly based on the first mode of vibration of dam which is most significant has been adopted for gravity dams like sardar Sarovar and Narmadasagar dams.

4.02 The most relevant aspects in Earthquake Resistant Design of dams are :

—Earthquake ground motion chracteristics.
—Method for computing dynamic structural response.
—Hydro-dynamic interaction.
—Foundation interaction.
—Strength parameters of materials used.

Out of these, attention is focussed to the last four aspects which are more relevant to the topic of this lecture.

4.03 Methods of computing dynamic structural response:

During an earthquake the magnitude of inertia forces acting on a structure depends upon the magnitude of acceleration, frequency contant, natural periods of the structure etc. As the structural acceleration increases the inertia forces increase which in turn may cause much larger stresses than in case of static loads. An important point to be reckoned with is the transient nature of higher stresses. It is this aspect which needs to be kept in view while taking decision regarding the structural safety of the dam for a particular set of chosen seiamic parameters.

For the purpose of simplicity, structures are analysed assuming linear behaviour while it is not so in reality. In case of linear analysis the methed of mode super position is used to calculate the mode shapes and natural frequencies of the structure. Once these values are calculated, by obtaining the corresponding modal participation factors the response of the structure can be obtained by referring to the given spectral accelerogram.

With the advent of high speed computers and advancements in the numerical methods, the nonlinear aspect can be taken care of. The nonlinearity may be due to the nonlinear material properties and/or increased viscous damping associated with larger strains and complexities of the foundation. The techniques of nonlinear analysis are available in references.

4.04 Hydro-dynamic interaction :

This is a very important aspect to be taken care of in modelling the earthquake response of a gravity dam. The most widely used method to account for hydro-dynamic interaction is the Westergaard's "Added Mass" approach[1]His solut;on includes the compressibility of water and assumes a rigid dam of infinite extent with a fixed foundation. Using the horizontal harmonic ground motion, he showed that resulting hydro-dynamic pressures are opposite in phase to the ground acceleration. and therefors, can be expressed in terms of equivalent inertia forces. This forms the basis of the "added mass" concept. A number of studies have been conducted to provide improved methods for including hydro-dynamic interaction in response analysis. Other forms of taking the reservoir effect is to represent water by fluid elements in FEM. Further refinements have been made by applying infinite elements to repesent the reserveir and foundation because of sitvery long dimensions and semi-infinte media.

4,05 Foundation interaction.

The unfavourable geological conditions have a signiticant impact on the overall behaviour of the system while dams on sound foundations have been analysed by assuming fixity at the base special cases like salal Dam foundation has been analysed taking into account the possible study along weak planes. When a gravity structure respond to an earthquake different styles of motion might occur (4,5). These could be :-

— sliding;
— sliding with uplifiting;
— rocky; and
— Rocky with uplifting

The different styles of motion, particularl the uplifting may consideraly alter the response of the structure to designer's advantage and this needs to be investigated further.

4 06 Strength parameters of materials used:

As per the existing ISI code the gravity dam has to be designed for no tension at the heel. With this ISI criteria gravity dams would provide a safe dam from seismic considerations. However, this criteria results in uneconomical sections and particularly so in high seismic zones. Keeping this in view the ISI have in their revised code permitted 1.5 kg/cm² tension in the heel in full reservoir conditons when pseudo-static method is used. In practice when dynamic stress analysis is used for DBE,tension upto6.25% and for MCE upto 12.5% of the allowable compressive stress is permitted. Some experiments were recently conducted at Bhatsa dam site to find out the tensile strength of uncoarsed rubble of masonry in tension. These experiments hava indicated the following strength parameters for uncoarsed rubble masonry:

CM	
1) 1:3	5.1 kg/cm²
2) 1:5	4.6-4.1 kg/cm²

The experiment conducted was in static condition.
A20 to 30% increase in strength with regard to the behaviour of the material under dynamic conditions is widely assumed. Some further investigation and experiment need to be conducted to evaluate in more detail the tensile strength parameter of the materials under dynamic condition.

At present the gravity dams are designed to keep the tensile stresses within the tensile strength under MCE conditions and undar DBE conditions. However, it can be argued that since the dam section is acting as a gravity structure with maximum compressive stresses at the toe or heel very low compared to its strength, and is designed with no tension at its base during static conditions the occurrence of cracks which close after the seismic event may be acceptable. The occurrence of cracks alter the response of the structure and increases its damping effects The post earthquake performance of dam may not be seriously affected. Some research studies of dam on this aspect could be worthwhile since it may be that the design criteria adopted now is conservative.

5 00 Earth and Rockfill Dams

5 01 Earth and rockfill dams are also affected by earthquake. The particle readjustment capacity of the material provides self-healing machanism and can be relied upon to take care of small cracks during the course of earthquake which is transient. Further the non-rigidity of the material forming the dam provides significant damping effect; thus reducing the impact to a great extent. It is for this reason that earth and earth-core rockfill dam appears to have an edge over rigid dam provided there are no liquifaction hazards associated with the material forming the dam foundation system. However it would be pertinent to note that most of the potential problems which

may develop as a result of earthquake action do not require always analytical treatment, but the application of common sense defensive measures to prevent deleterious effects. From this, it follows that the design of earth and earth-core rockfill dams has to be tackled on two fronts :

1) Defensive measures.
2) Analytical measures.

5.02 Defensive measures :

A thorough knowledge of the possible ways in which earth dam may fail during an earthquake is essential for developing Earthquake Resistant Design. These are :

— Failure due to disruption of the dam by major fault movement in the foundation.
— Slope failures induced by ground motions.
— Loss of freeboard due to differential tectonic ground movements.
— Sliding of the dam on weak foundation materials.
— Piping failure through cracks induced by the ground motions.
— Overtopping of the dam due to seiches in the reservior.
— Overtopping of the dam due to slides or rockfalls into the reservoir.
— Overtopping of the dam due to failure of the spillway or outlet works.

Many of the above potentially harmful effects of earthquakes on earth and rockfill dams can be eliminated by adopting the following defensive measures :

— Provide ample free board to allow for settlement, slumping or fault movements.
— Use wide transition zones of material not vulnerable to cracking.
— Use chimney drains near the central portion of embankment.
— Provide ample drainage zones to allow for possible flow of water through cracks
— Use wide core zones of plastic materials not vulnerable to cracking.
— Use a well graded filter zone upstream of the core to serve as a crack-stopper.
— Provide crest details which will prevent erosion in the event of overtopping.
— Flare the embankment core at abutment contacts.
— Locate the core to minimize the degree of saturation of materials.
— Stablize slopes around the reservoir rim to prevent slides into the reservoir.

— Provide special details if dangers of fault movement in foundation.

5.03 Analytical measures :

The pseudo-static method has been in vogue for the past 40 years or more and been used with considerable success in designing of dams and most of the engineers are conversant wifh this concept. In this method the effect of an earthquake on a potential sliding mase are represented by an equivalent static horizontal force determined as the product of a seismic co-efficient K and the weight of the potential sliding mass. Generally, if the computed factor of safety in this approach is equal to some pre-determined value equal-to or greater than one, the embankment section is considered safe although the acceptable value is largely based upon an evaluation of many factors and ultimately on the judgement of the engineer.

In the pseudo-static method the selection of appropriate seismic co-efficient is a difficult task. However, where the provisions for drainage against development of excess of pore pressures are provided or the soil is such that degradation of strength under dynamic action is negligible this method is stil a sound and widely followed practice.

The pseudo-static acceleration can either be assumed uniform along the length or trapezoidal. At present it will be safe to check the section for both assumptions.

The 1971 San Fernando earthquake brought the San Fernando Dam to near failure. It is interesting to note that the seismic stability of the dam hed been evaluated only five years before the earthquake and a reputable design review agency and consulting board had concluded that it was safe against any earthquake to which dam might be subjected to. Assuming a seismic co-efficient of 0.15 the computed factor of safety for tne San Fernando Dam was between 2 and 2.5, yet the upper part of the embankment moved between 5 and 7 ft. downstream during the earthquake. Fortunately, the reservoir water level was much below. Thus, no catastrophic damage tookplace The failure of embankments in cohesionless soils due to excess pressure indicates that in such soils failure like the one above have to be safeguarded.

With all fhe sophistication in the design, the design of earth dam still remains an art to a certain extent The performance of completed dams in earthquake are relevant for taking a view on the design aspect.

Professor H. Bolton Seed [6] in his Nineteenth Rankine Lecture has made the following observations after a close study of embankment dam performance during earthquakes which are relevant :

(a) Hydraulic fill dams have been found to be vulnerable to failures under unfavourable conditions and one of the particularly unfavourable conditions would be expected to be shaking produced by strong earthquakes. However, many hydraulic fill dams have performed well for many years and when they are built with reasonable slopes on good foundtions they can apparenty survive moderately strong shaking—with accelerations upto about 0.2g from magnitude 64 earthquakes with no harmful effects.

(b) Virtually any well-built dam on a firm foundation can withstand moderate earthquake shaking, say with peak accelerations of about 0 2g, with no detrimental effects.

(c) Dams constructed of clay soils on clay or rock foundations have withstood extremely strong shaking ranging from 0.35 to 0.8g from a magnitude 8½ earthquake with no apparent damage.

(d) Two rockfill dams have withstood moderately strong shaking with no signifificant damage and if the rockfill is kept dry by means of a concrete facing, such dams should be able to withstand extremely strong shaking with only small deformations.

(e) Dams which have suffered complete failure or slope failures as a result of earthquake shaking seem to have been constructed primaily with saturated sand shells or on saturated sand foundations.

(f) Since there is ample field evidence that wll-built dams can withstand moderate shaking with peak accelerations up to at least 0.2g with no harmful effects, we should not waste our time and money analysing this type of problem-rather we should concentrate our efforts on those dams likely to present problems either because of strong shaking involving accelerations well in excees of 0.2g or because they incorporate large bodies of cohesionless materials (usually sands) which, if saturated, may lose most of their strength during earthquake shaking and thereby lead to undesirable movements.

(g) For dams constructed of saturated cohesionless soils and subjected to strong shaking, a primary cause of damage or failure is the build-up of pore water pressures in the embankment and the possible loss of strength wich may accrue as a result of these pore preasures. It is not possible to predict this type of failure by pseudo-static analyses, and other types of analysis techniques are required to provide a more reliable basis for evaluating field performance,

5.04 Dynamic Response Approach :

The approach has been pioneered by Newmark[8]. Essentially it considers the embankment material to be rigid-plastic in nature and for movements of soil mass to occur along a well-defined surface. The method involves the determination of a yield acceleration, i. e. an acceleration at which sliding will begin and the computation of displacement that develop in the time intervals when this acceleration is exceeded. However, Prof. Seed has struck a note of caution that determination of appropriate value of yield acceleration becomes extremely difficult for soil in which pore pressure changes develop as a result of shear strains induced by the earthquake.

Prof. Seed [7] has suggested an alternative approach. This is based on :

(1) a determination of the stresses acting on soil elements within an embankment both before and during an earthquake;

(2) subjecting typical soil samples in the laboratory to the same sequence of stress changes experienced by corresponding elements in the field and observing the resulting deformation; and,

(3) estimating deformations of the slope from the observed deformation of the soil elements comprising it.

The above method takes into account;

(i) time history of forces developed in an embankment or slopes during an earthquake;

(ii) the behaviour of the soil under simulating earthquake loading conditons; and

(iii) the desirability of evalauting embankment deformations rather than a factor of safety.

The finite element lechnique in the design of rockfill dam would provide the designer with qualitative information due to limitations on the stress-relationships of soils and rockfills and assist him to distribute the material avaliable at the site and to specify their placement in the embankment. For dams of length 'L' greater than 5 to 6 times their height (H) except in the vicinity of the abutments the assumption of plane strain state namely a two dimensional analysis would hold good. However, in narrow gorges when the 'L'/'H' is leas than 5, it is necessary to use the results of three dimensional analysis as considerable fraction of the loads are transferred to the abutments and corresponding deformations and shear stresses are reduced.

6. CONCLUSIONS

From the foregoing paragraphs it become evident that earthquake resistant design calls for multi-disciplinary approach, as it involves assesment of seismic potential of the dam site, seismic response of the structures proposed etc. and the study of natural behaviour. Refinement in design of techniques is called for since new dam sites are located in highly seismic zones riddled with complex tectonic features. The development of techniques of dynamic analysis has to be preceded by development of realistic constitutive laws of the materials involved. Experimental work has not kept up with the analytical work. The devlopment and utilisation of the centrifuge for testing of structural models will perhaps help in the confirming the applicability of various constitutive laws with combined work of laboratory testing, development of analyses and field monitoring that will enable rapid developments to ensure safe and economic structures.

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