EARTH DAMS SUBJECTED TO EARTHQUAKES

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SYNOPSIS

This paper presents, factors affecting the stability of an earth dam under earthquake forces with particular reference to Ramganga dam, 122 m high. Field blasting tests to determine the dominant period of ground and other necessary data alongwith the results of model tests on a large shock vibration table have been described. The model tests offer a good scope for the qualitative study of the problem of stability under earthquake loads. It has been shown that the variation of acceleration with the height of the dam is similar to that predicted theoretically.

INTRODUCTION

The importance of earthquake loads on earth dams has enhanced recently when a number of high earth dams are being planned in seismically active zones in different parts of the World. In India, Ramganga dam about 122 m high, and Beas dam about 100 m high, belong to this category. All of them are either close to active faults or so situated that they are likely to experience a shock of moderate or severe intensity in their life time. The problems connected with behaviour and design of earth dams against earthquake forces are many and no clear cut and quantitative answer to almost any of them is available. Efforts have been directed towards theoretical analysis of idealized cross sections (1, 2) based on theory of elasticity, and model analysis and model testing (3, 4). Because of the very nature of the earthquakes, no field study is apparently possible under actual loading conditions. Further, because of huge mass of earth dam involved, no field testing is economically feasible and even if vibrations are caused by blasting in the vicinity or by placing an eccentric vibrator on the top of dam, it will be difficult to determine the portion of the dam actually participating in the vibrations that we record on the instruments. Thus theoretical analysis, which must be based on many assumptions, difficult to realise in practice, lack the backing of confirmation by field data. Although model studies suffer from certain disadvantages, models offer a useful tool in studying the effect of certain variables.

In this paper, factors affecting the stability of an earth dam under earthquakes have been discussed with particular reference to Ramganga dam. Also results of field observations and model study of certain typical sections on a large shock Vibration Table 5.2 m x 2.8 m have been presented.

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FACTORS AFFECTING STABILITY

An earth dam may fail in any one of the following ways when subjected to an earthquake shock (2) :-

i) Compaction of dam and/or foundations and consequently slumping and possible over-topping by waves.

ii) Sliding of the dam on its base when the overall earthquake acceleration exceeds the coefficient of friction between the dam and the foundations.

iii) Separation of the dam from its abutments due to unequal rigidity of the dam and the abutments and consequent out of phase vibrations (Similar would be the situation when a concrete or masonry spillway section joins the earth structure) or shearing of the dam across its section if a fault crossed it (which should be rare if proper geological investigations have been carried out before selection of a site).

iv) Slipping of the slopes resulting in longitudinal cracks near the top due to the horizontal and vertical inertia forces.

v) Liquefaction and failure of foundations.

Excessive settlement of the dam and foundations and over-topping by waves may be prevented by increasing the density of section and foundation materials and providing additional free board, while shear keys at the base will check sliding on the base. Further, a dam would not normally be constructed right across a fault. The joint of the dam with abutments needs be strong, and it would perhaps be advantageous if the dam section is altered near the junction in order to adjust its stiffness and thereby reduce the out-of-phase shears. Slipping of the slopes may result from various reasons discussed below. Liquefaction and failure of foundations are beyond the scope of this paper.

Slope failure : In order to ascertain if slope failure is likely to take place in an earth dam, the size of shock expected in the region is assumed and the dominant period of vibration determined.

For analysis of the stability of the sections, the following factors need be considered :-

i) Strength characteristics of soils under dynamic loads.

ii) Pore pressures set up during dynamic loading.

iii) Acceleration pattern within the dam.

The strength of soils usually increases with increase in rate of loading. Quantitative values have also been assigned to the increase in strength under purely dynamic loading, but in an actual dam, the load is static as well as dynamic, the latter being a fraction of the former. Therefore the actual increase in strength under the combined loads remains undetermined. The information simulating actual loading conditions is scanty. Arbitrary increases of strength have been adopted in practical design work.

Pore pressures present one of the most intricate problems in stability analysis under dynamic loads. The major difficulties are the ascertaining of its magnitude and its rate of dissipation. Some information is available on magnitudes of pore pressures developed in non-cohesive dense sands under fast rates of loading (5, 6). However, the behaviour of earth dam models of dense sand with respect to their settlement do not conform to that predicted on the basis of laboratory tests (4). Patel (7) has suggested a procedure to compute pore pressures in earthen embankments due to hydrodynamic pressures based upon his tests in an electrical analogy tank. This gives instantaneous values of pore pressures on the upstream slope of the dam for the full reservoir condition only. The strength of the section will thus be affected by the nature of pore pressures induced due to shock loading. This leaves many other problems unsolved for example earthquake forces will affect the pore pressures inside the dam irrespective of the effect of hydrodynamic pressures. Further, the pore pressures get dissipated with time either during the period of shock itself or after it. If the dissipation of pore pressure leads to greater stability its effect could be neglected, but if it leads to instability as it would be in dilatant soils, its effect has to be kept in view. However, if the pore pressure dissipation occurs after the shock, its effect may be important in determining the strength in a subsequent shock if it occurs before the conditions are normalised.

Most of the codes of practice provide for a uniform horizontal force in the design of earth dams against earthquake forces. It has been shown (2) that for the same total force on the dam height, the intensity of force allowed in the top quarter can be 62.5 percent higher than the corresponding uniform force.

In addition to these factors, damping of the soil and position of the core also affect dynamic stability of an earth dam. If the soil offers large damping, the amplitude of deformation will not build up to a high value. Although no account is taken of deformations in a stability analysis, it is well known that failure will occur only if a certain amount of deformation has taken place.

Failure of a section may take place as in Figure 1 a and b. This represents failure of the down stream slope. In figure 1 a, a portion of the downstream slope has moved towards the toe. Small movements of this nature are not harmful. The resulting section shown dotted is stronger than the initial section since the mass of soil has been transferred to a more stable position, and the section can be repaired.

In figure 1 b, the failure of slope is of catastrophic nature especially if the water waves are high enough to overtop the dam.

During draw-down, the loading conditions are severe for the upstream slope the failure of which is more likely if an earthquake occures in such condition. But the failure will be inconsequential except for expenditure involved in repairs as long as water in the reservoir does not over top the dam. It may probably be worthwhile spending the money in repairs to a section later rather than invest it initially in making the section strong. Thus excepting for the damage shown in Figure 1 b, the other two types could be considered as permissible damage. It is easy to show that such permissible deformations would absorb tremendous amount of energy and no great harm to such structures may occur. The only case is which a high factor of safety in design is called for is illustrated by Figure 1 b. In this case higher freeboard than is normally recommended would be essential.

A section with sloping core is more stable than the one with central core. In the latter, the upstream shell, the core and the downstream shell behave as three units of different rigidity and have different periods of vibration. Hence these have a tendency to vibrate out of phase and separate out. A section with the sloping core has the core resting on the downstream shell and the upstream shell in turn resting on the core. This leads to a superior bond of the three units and the section behaves as one mass, and leads to greater stability.

RAMGANGA DAM

This dam is planned in a region affected seismically due to the faulting and folding of the Himalayan and other subsidiary mountain ranges. There are several faults near the site and some others at some distance away (8). In the last 130 years or so, no earthquake of substantial size has originated from the faults in the immediate neighbourhood of the proposed site, but the faults lying further away have been active. Recent geological investigations and occurrence of earthquakes seem to indicate that there are perhaps some faults deep down the alluvium. The Earthquake Research School, Roorkee, placed a Sprengnether seismograph near the site of the dam on firm rock for some time. It did not record any tremors originating from any of the closeby faults, but it did record some micro tremors originating from a fault at a distance of 50 miles and another from a fault about 120 miles away. Geological evidence and the site observations indicate that the nearby faults are dormant and the nearest active fault is about 50 miles from the site which may cause future shocks. A designer then needs to estimate the size of the earthquake which may be expected from these faults. Expressing in terms of Richter's magnitude, the biggest earthquakes that have occurred, are 6.7 and 7.5 with epicenters 90 miles and 130 miles away, respectively. The past records indicate that the maximum intensity felt near the site is on the lower side of MM VIII. Such an earthquake does not cause much harm to an earth dam which is a very stiff structure. Further due to plasticity of the material, it absorbs energy without appreciable damage.

Based on these assumptions and using magnitude-distance-acceleration curves (9) and the Standard Spectrum Curves the design coefficient works out to 15 % g. This could be applied to the mass in the top region and reduced towards the base according to the indications of the model studies.

EXPERIMENTAL WORK

Field Study : Dominant period of ground is determined to ascertain if the natural period of the dam is not close to it. Also, this information is required for model tests in which the periods have to be reduced in a certain ratio to simulate field loading (3). To determine the dominant period of ground, blasting tests were carried out with special gelatin 80 percent. The amount of charge used was 10, 20, 50 and 100 lbs.

In all twelve explosions were fired, the details of which are as follows;-

TABLE 1

Distance from observation site ft.	No. of blasts	Quantity of Explosive lbs.
500	2	10
500	1	20
500	1	50
1050	2	20
1050	2	50
3000	2	100
3000	2	200

For determining the accelerations, particle velocity and displacements caused by the waves, acceleration, velocity and displacement were recorded, along the axis of the dam and perpendicular to it. Velocity and displacement pick-ups were arranged to measure the velocity and displacement of the rock particles in a direction perpendicular to the dam axis.

Typical records of acceleration, velocity and displacement gave values of P and S wave velocities, dominant period of vibration and the elastic constants.

Model Tests : Model studies of Ramganga dam and a sand section were carried out on a shock vibration table having a free movement in one horizontal direction. The following observations were made :

i) Section of Ramganga dam. A model of Ramganga dam was constructed from the materials obtained from the site. The linear scale ratio was 1/200. The blows given had the intensity from 0.2 g to 0.5 g. The cracks developed on both the surfaces of the slopes, the depth of which, was 1.5 in. to 3 in. parallel to the axis of the dam. This pattern was similar to the cracks reported about ONO dam in Japan (10) during 1923 earthquake. For the ultimate load situation, the behaviour of this model represented that of an actual dam qualitatively.

Another observation was that the core and shells on its two sides did not vibrate as a homogeneous mass. By visual observation these could be seen to be vibrating out of phase quite often resulting in a crack along the joint. The depth of this crack was one fourth to one-third the height of the model. This confirmed the observations made earlier about the desirability of the sloping core.

ii) A Section of sand with steep slopes as shown in Figure 2 was next tested. The slope corresponds to the angle of repose. The first shock with 0.2 g caused only a few cracks on both the slopes, where as a second shock of similar intensity caused slumping of slopes as shown dotted in the figure.

iii) Another section of sand with 30° slopes was tested with some acceleration pick-ups embedded close to the top in one test and close to the bottom in another, Figure 3,4. From the records, the acceleration pattern with height of the dam was plotted as in Figure 5. Theoretical values calculated in (2) have also been plotted. Also values reported by Seed and Clough (4) have been included in this plot. The experimental values are very close to the theoretical ones.

Further work on the stability of embankments and strength of soils is currently in hand at the School.

CONCLUSIONS

One of the significant conclusion which can be drawn from these preliminary tests is that the technique of model testing offers a good scope for the qualitative study of stability problem under earthquake loads. The pattern of acceleration with the height of dam in these tests is very similar to the theoretically predicted one.

ACKNOWLEDGEMENT

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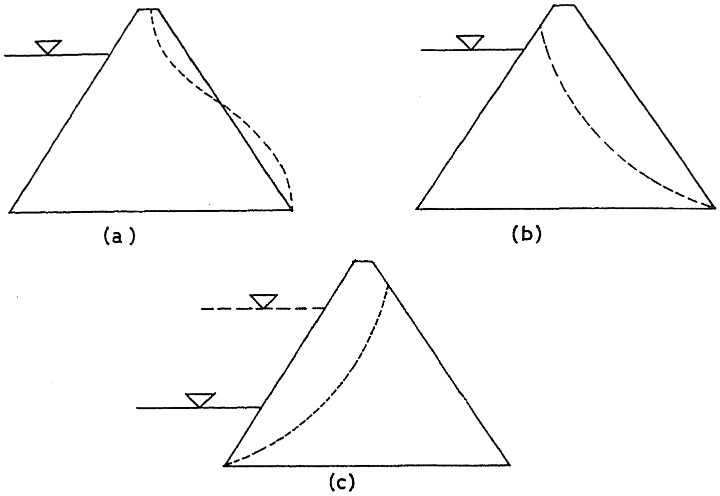

FIG.1 FAILURE OF SECTION

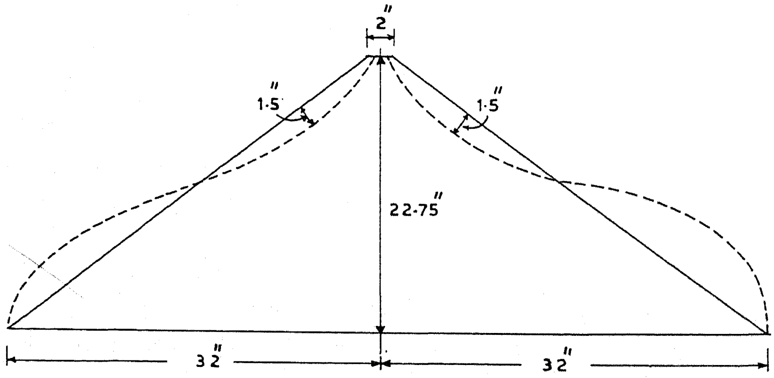

FIG. 2 TYPICAL SECTION (III)

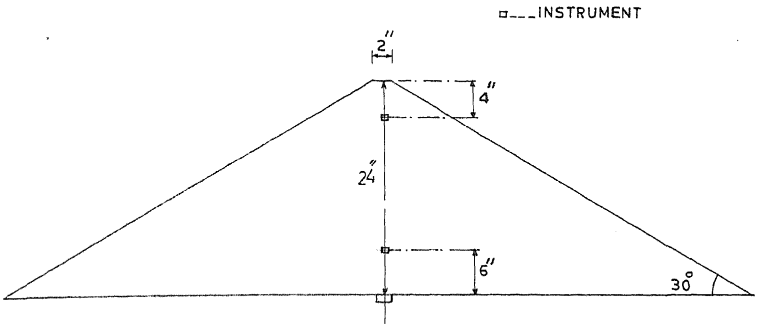

FIG. 3 TYPICAL SECTION (II)

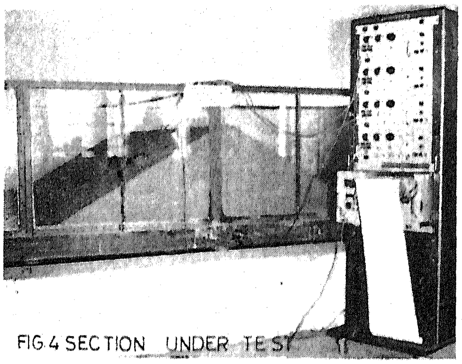

FIG.4 SECTION UNDER TEST

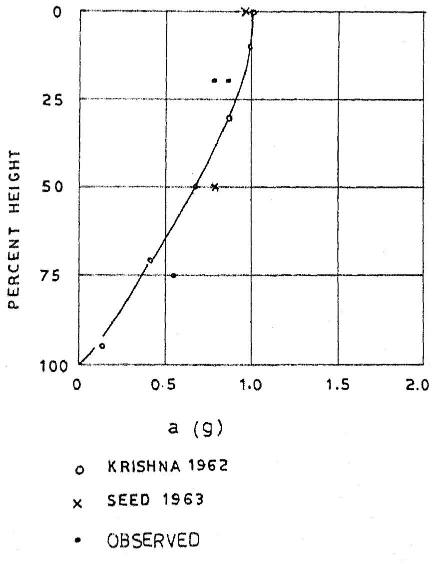

FIG. 5 ACCELERATION PATTERN

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BY J. KRISHNA AND S. PRAKHASH

DISCUSSION

BY N. N. AMBRASEYS

At the present stage of knowledge, my opinion for the use of models of earth and rock-fill dams is, to verify analytical methods applied to the models themselves rather, than use model results to infer the seismic behaviour of the prototype. The experience so far gained from model tests suggests that there is a great deal of work to be done before a satisfactory method of model testing is produced. Also, the available material suggests that results from model tests on rock-fill and earth dams are not applicable to the full scale prototype, particularly to earth dams.

One or more of the following discrepancies are usually involved in model tests of rock-fill dams which are of considerable consequence:

I) A slight amount of capillary tension in the model would represent an extremely large apparent cohesive strength of the rock-fill in the prototype. For instance, for a scale ratio of 1/300, capillary tension of -o.1 1lb/in^2 in a sand of $\phi' = 30^{o}$ will represent in the prototype a cohesion in the rock-fill of 15 lb/in^2.

II) Under very low confining pressures the model material of a rock-fill (sand) will show apparent cohesion of o.2 to 10 lb/ft^2. Slight variations in the humidity, density or angularity of the sand will reflect changes in the value of this apparent cohesion.

III) Lack of similitude in the model with respect to contact forces. In moist sands the extremely low intergranular forces in the model will be of the same order of magnitude as the capillary forces. There is evidence to show that an effective ambient pressure of, say, one atmosphere, acting on a rock-fill mass will result in setting up contact forces of the order of 10^3lbs. The same pressure, acting on a mass of dry sand will set up intergranular forces of the order of 10^{-4}lbs., and although the grain size of the prototype material is scaled down, the contact pressures are not.

IV) Moreover, models usually lack similitude with respect to the crushing strength of the rock material. The grains of the sand in the model are as strong, or probably stronger, than the rocks in the prototype. For instance, if the rock in a dam, scaled down 300 times, had a crushing strength of 10,000 lb/in^2, the strength of the grains used in the model should have been about 26lb/in^2. The tensile strength of the rock is also important as crushing in many instances occurs due to cataclastic stresses (a mechanism similar to that of the Brazilian test). A grain of sand is likely to have fewer flaws and higher tensile strength than a piece of rock.

This lack of similitude, of course, would have been irrelevant to the scaling of the crushing strength of the rock-fill should the individual grains in both model and prototype have been absolutely rigid. But, under the overburden pressures involved in a large dam, the rock will crush, and the structure will settle more than any other type of fill structure of the same size, which shows that rock is not absolutely rigid. It is conceivable that crushing will be less pronounced in fills with rounded rocks and pebbles than in fills of sharp-edged rough-shaped rocks, yet it will be an effect present in any structure of this kind.

V) As a result of these effects, there will be lack of similitude in the shear strength of the fill material. With increasing pressures, the shear strength envelope will tend to flatten. Consequently, above a certain pressure the strength envelope of the prototype material will lie below that of the material of the model.

VI) Lack of similitude in pore water pressures in the core and fill material. The scaling of pore water pressures requires the void ratio, and the stress-strain paths of both materials to be scaled to the same ratio. In partly saturated fills the problem of scaling the point of cavitation in the two materials is extremely important.

VII) The strain-rate effects in the model depend not only on the proper modelling of the time-rate of strain, but also on the scaling of the strains. This in turn requires similarity in the model with respect to the deformation characteristics of the prototype in plane strain.

VIII) Extremely small variations in the shear strength properties of the model will reflect very large prototype deformations. There is evidence to suggest that, in the case of dry sand, the angles of friction are higher by a few degrees for dense sand compared with angles of friction obtained from triaxial tests on saturated sand under the same test conditions. The presence of water at the intergranular contacts may alter the coefficient of friction mobilised during sliding, and also that the structure of the sand depends on the method of deposition, i.e. placed oven dry, and then saturated, placed wet under water etc.

IX) Kinematic friction developing between mineral surfaces is generally smaller than the static friction.

X) The frictional resistance that can develop between quartz surfaces increases as surface moisture increases.

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BY J. KRISHNA AND S. PRAKHASH

QUESTION BY: **N.N. AMBRASEYS - UNITED KINGDOM**

I feel model dams are unsatisfactory for interpreting earthquake response in the prototype, and would like the authors' comments on how they scale down soil particle size etc.

AUTHORS' REPLY: Dr. Ambraseys has pointed out a number of discrepancies between the results that a model will give and the behaviour that a prototype is expected to have during an earthquake. We have no hesitation in accepting that. Getting exact similarities for quantitative purposes from a model will be extremely difficult. It may, however, be pointed out that it is possible for the model study to provide relative characteristics of different profiles with respect to certain properties for which the model has been designed. It is true that for some properties a model cannot give reasonable similarity, but for others involved in a study of this kind, this is possible. The authors have obtained a pattern of variation of acceleration along the height quite successfully. Further, overall failure of the model had the same features as those which were indicated in the failure of ONO Dam in JAPAN in the KANTO Earthquake of 1923. That would indicate that the forces applied and the overall behaviour of the model had some similarity with the actual earthquake exerting forces on the prototype. The models of this kind do qualitatively indicate the possible position of the cracks. It is not possible to claim much more from these tests at present.

QUESTION BY: **A.S. YAGUE - SPAIN**

I believe that a special danger is not involved in the case of waterwaves overthrowing the earth dam. Only one or two waves are produced and the resulting landslide due to an earthquake moves slowly.

The recommendation of a higher freeboard generally imposes an economic burden.

AUTHORS' REPLY: We feel that the overtopping of earth dams by waves will be serious and could be expected if the dam and the lake oscillate out of phase with each other, which is quite likely. Higher free-boards particularly on the upstream side should be useful but the additional cost could be minimized by adjusting slope in the upper region of the dam.

QUESTION BY: **K. KUBO - JAPAN**

What were the characteristics of the Ramganga dam foundations; hard, medium or soft?

AUTHORS' REPLY: The foundations consist of weathered and fissured rocks with clay bands inclined at a slope almost parallel to the upstream slope. The characteristics of the foundations of the dams may be classified as "Medium".

COMMENTS BY: **N.M. NEWMARK - U.S.A.**

I should like to ask Professor Krishna what damping factor was used in his calculations. In earth, as well as in concrete and steel structures, the amount of damping is dependent on the magnitude of strains or deformations. In general, reinforced concrete structures and steel structures have damping factors of the order of about 1 to 2 percent critical or less in the working stress range, but as they approach yielding the damping goes up to 5 to 10 percent of the critical value. In soils, for very small oscillatory movements, the damping may be small or almost negligible, but probably approaches 10 percent or maybe even higher values when the magnitudes of motion approach failure in shear or involve local shear failures. In records of very small motion in the soils under Oakland Bay, for example, I can interpret these to indicate that damping was less than 0.5 percent, although I am sure that if these deformations had been larger, the damping factors would have been very much higher.