Liquefaction potential of sand layers under a proposed dam

Capacité de liquéfaction de couches sableuses sous un barrage conçu

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SYNOPSIS: According to design the shoulders of the proposed earth and rock fill dam would be founded directly on the river alluvium in the valley. Drilling in the river bed indicated the presence of sand layers interbedded in the coarser alluvial deposits. Standard Penetration Tests were carried out in the sand layers and their average standardised values were obtained. Studies of the test results indicated that the sand layers are likely to liquefy in an MCE under level ground conditions. In order to increase the stability of the dam, weight berms both on u/s and d/s between the toe of the main dam and cofferdams were added. Stability analysis for the post earthquake condition showed that adequate FOS were available for the confined sand layers. However, in case of surface sand layer under the u/s toe of dam, the FOS against sliding was low. It was decided to remove the sand layer from a limited stretch and replace it with well compacted sandstone fill.

1 INTRODUCTION

The dam is about 260 ft. (80 m) high earth and rock fill. It shall have positive cutoff with the clay core taken down to the bed rock while the u/s and d/s shell would be resting on 90 ft. (27 m) thick river alluvium. Fig.1 shows a typical cross section of the dam. Drilling carried out in alluvium in the river bed indicated the presence of sand layers interbedded in the sandy gravels, cobbles and boulders under the shoulders of the dam. It is known that during earthquakes there is a build up of excess hydrostatic pressure in saturated cohesionless materials due to the application of shear stresses induced by the ground motions. Liquefaction resulting in loss of strength occurs if the increase in the pore water pressure equals the overburden pressures. Based on the S.P.T results it was concluded that the layers are likely to liquefy in an MCE under level ground conditions. The paper describes briefly the field investigations, evaluation of liquefaction potential of the sand layers and post-earthquake safety of the embankment.

2 FIELD INVESTIGATIONS AND TESTS

During feasibility and design studies 35 holes amounting nearly 4000 ft. (1219 m) of drilling were done in the river bed. As a result of investigations, 5 sand layers given in Table 1 were identified. Fig.1&2 show x-sections of the river bed alluvium containing the sand layers.

Table 1. Location of sand layer

Layer	Depth from surface (ft.)	(m)	Thickness (ft.)	(m)
SL1	0-30	0-9	5-30	2-9
SL2	30-55	9-17	5-15	2-5
SL3	55-88	17-27	5-20	2-6
SL4	15-25	5-8	5-10	2-3
SL5	125	38	1-5	0.3-2

2.1 Particle size

From the gradation analyses, the material can be grouped into two categories (a) gravelly sand (b) sand without gravels. Majority of samples have fine content less than 5%. The material is generally fine to medium sand with D_{50} ranging between 0.15 to 0.35 mm.

2.2 Undisturbed samples

Various types of undisturbed samplers were tried but only a couple of undisturbed samples could be obtained. The dry density of the undisturbed sample was about 100 lbs/cuft.(16 KN/m^3). From the maximum and min. dry densities of the material obtained in the laboratory, this corresponds to a relative density of 67%.

2.3 Standard penetration testing

The type of equipment used and the procedure followed has a significant influence on the blow count. Efforts were made to improve the techniques and equipment so that a more dynamically

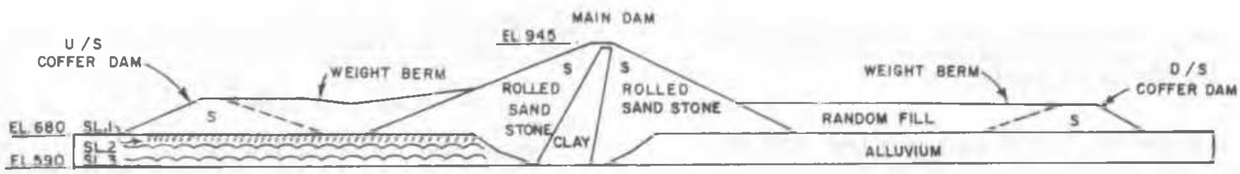

Figure 1. Typical cross section of the dam

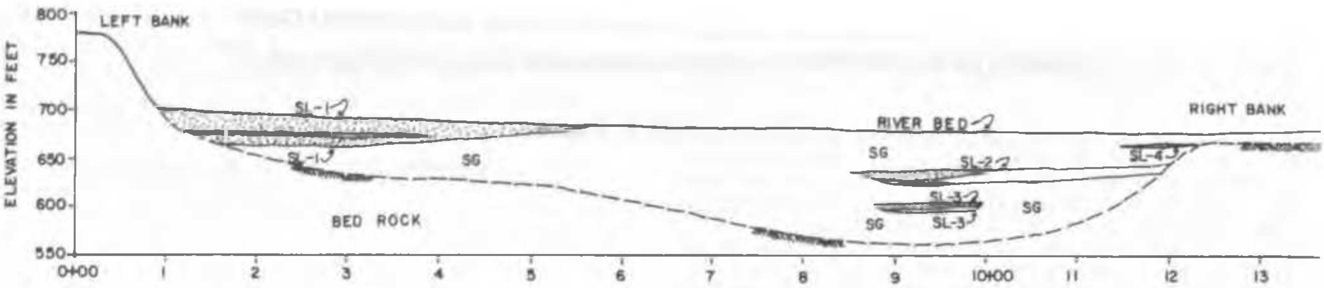

Figure 2. L-Section of river alluvium containing sand layers

efficient method of transferring energy to the rods was obtained. The blow count recorded during 35 SPTs in the sand layers varied from 7 to 38 with most of the values between 10 and 25.

3 EVALUATION OF LIQUEFACTION POTENTIAL

Out of the five sand layers only SL1, SL2 and SL3 were considered sufficiently extensive in areal extent to have any implications for the dam. Therefore only these layers have been considered in the analysis. The correlations developed by Seed (1984) have been used in the study.

3.1 Method of analysis

The analysis included the following steps:

1. Standardise the observed 'N' values in the SPT to energy ratio of 60%.
2. Determine from available correlations, the cyclic shear stresses that would develop in the sand layers in order to cause liquefaction.
3. Determine the average cyclic shear stresses induced by the earthquake ground motion in the sand layers.
4. Determine

$$F.O.S = \frac{\text{Limiting Cyclic Shear Stress}}{\text{Induced Cyclic Shear Stress}}$$

3.2 Standardization of 'N' values

Observed 'N' value was corrected for overburden pressure by the equation:

corrected value $N_1 = CN \cdot N$

with CN = Correction Factor $= \frac{3}{2 + \sigma v'}$

$\sigma v'$ = Vertical effective stress

The SPT 'N' values were normalized to an energy ratio of 60%

$$(N_1)\,60 = \frac{ER_r \; N_1}{60}$$

ER_r = Rod energy ratio for method used in investigation = nd x ERV

nd for 16 kg anvil = 0.7

The average (N_1) 60 values obtained for the three sand layers are given in Table 3.

3.3 Cyclic shear stresses induced by earthquake

The average cyclic shear stresses induced by an earthquake on horizontal surfaces of a deposit can be expressed by the following equation:

$$\tau_{av} = 0.65 \frac{A_{max}}{g} \sigma_o \, r_d \quad \text{Seed (1984)}$$

where Amax = Maximum ground acceleration

σ_o = Total vertical stress

r_d = Stress reduction factor

The average cyclic stress ratios (defined as τ/σ_o' where σ_o' = effective vertical stress) induced in the sand layers by an MCE (Amax = 0.4 g) are given in table 2.

Table 2 Cyclic stress ratios induced by MCE

Sand Layer	Assumed av. depth ft.	Assumed av. depth meter	Induced Cyclic Stress Ratio
SL1	20	6	0.46
SL2	45	14	0.39
SL3	70	21	0.39

3.4 Cyclic stress ratio causing liquefaction

Field performance data available for soil deposits which have liquefied under known conditions of earthquake shaking have been correlated to standardised values of (N_1) 60 by Seed (1984). The basic correlation developed by him is for M=7.5 earthquake. For earthquakes of other magnitudes he suggests adjustments which are based on number of cycles representative of the events. For the dam MCE corresponds to M = 7 event and therefore the induced cyclic stress ratios for various (N_1) 60 value given in the correlation were adjusted by a factor of 1.1.

The curves proposed by Seed and Skempton are shown on Fig.3. Cyclic stress ratios corresponding to (N_1) 60 values were determined from these curves. These values are however valid for effective vertical stress of $1T/ft^2$ and need to be corrected for higher values. The correlation factor can be expressed by the following equation Skempton (1985):

$$\frac{1}{C\sigma} = 0.85 + 0.15\,\sigma v'$$

where $C\sigma$ = Correction factor

$\sigma v'$ = Vertical stress (effective)

The corrected limiting cyclic stress ratios calculated for various sand layers are as below:

Table 3. Limiting stress ratios in sandy layers

Sandy Layer	(N_1) 60	Limiting shear stress ratio
SL-1	14	0.17
SL-2	21	0.24
SL-3	18	0.18

3.5 Factor of safety against liquefaction

The factor of safety against liquefaction was calculated as the ratio of the limiting cyclic stress (Table-3) to the induced cyclic stress ratio values (Table-2). These are presented in Table-4.

Table 4. Factor of safety against liquefaction

Sandy Layer	Factor of Safety
SL-1	0.36
SL-2	0.62
SL-3	0.62

From the above it can be seen that liquefaction of the sand layer can be expected under level ground conditions.

4 CONDITION AFTER CONSTRUCTION OF MAIN DAM

Dynamic analysis of the dam gave the following results:

1. Liquefaction is likely to occur in the Sand Layer SL-1 in an area extending between 500 and 1100 feet(152-335 m)from the centre line of the main embankment below the u/s weight berm and coffer dam while all of this sand layer below the d/s fill is prone to liquefaction.
2. Liquefaction is not likely to occur in Sand Layer SL-2 according to Skempton's curve.However, according to Seed's approach, Sand in layer SL-2 is likely to liquefy below the u/s 700 to 1100 feet (213-335 m)from the centre line of the main embankment. The Sand Layer SL-2 below the d/s fill will also liquefy.
3. Sand Layer SL-3 will liquefy in an area between 700 to 1100 feet (213-335 m) from the centre line below the u/s fill, using either the Seed's or Skemption's curves.

It was decided to add weight berms both on u/s and d/s between the main dam and the cofferdams. Enough material from excavations would be available for the weight berms.

4.1 Post earthquake safety of dam

Assuming that the sand layers in the river bed will liquefy in an MCE, the post earthquake safety of the dam in terms of static factor of safety against sliding and deformation was evaluated. Residual strength of the sand layer just after an earthquake found from Seed's relation was SL-1 = 600 Psf (0.29 kg/cm^2) SL-2 = 2000 Psf (0.98 kg/cm^2) and SL-3 = 1200 Psf(0.58 kg/cm^2).

It was seen from the analysis that under u/s shoulder of the dam adequate factors of safety were available against sliding along SL-2 & SL-3. It was also seen that FOS greater than unity was still available even if there was complete loss of strength of the sand in these layers. However in the case of surface sand layer SL-1 below the u/s shoulder the FOS against sliding was low and the expected deformations excessive.

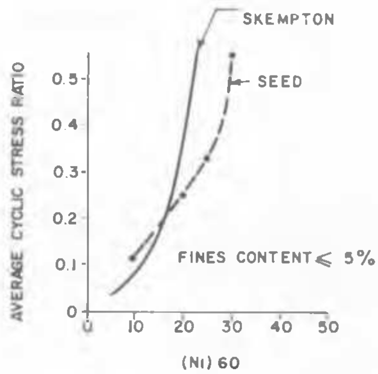

Fig.3 Average cyclic stress ratio vs SPT(N_1) 60 after Seed and Skempton

4.2 Foundation Improvement

The situation can be improved quite effectively by removing the surface sand layer from below the u/s toe of the dam over a length necessary to achieve the required FOS and replacing it with a well compacted sandstone fill. Similarly limited excavation of the sand layer, if present will be sufficient at the d/s toe of main dam to achieve the required factor of safety.

REFERENCE

Seed et al. (1984). The influence of SPT procedure in soil liquefaction resistance evaluations. Report No.UCB/EERC-84/15 Oct. 1984