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Effects of Earthquake Induced Liquefaction of Sediments Stored Behind Concrete Dams

Peter M. Byrne
University of British Columbia, Vancouver, B.C., Canada

Li Yan
University of British Columbia, Vancouver, B.C., Canada

T. Srithar
University of British Columbia, Vancouver, B.C., Canada

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Peter M. Byrne
Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada

Li Yan
Department of Civil Engineering, University of British Columbia Vancouver, B.C., Canada

T. Srithar
Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada

SYNOPSIS: Earthquake induced liquefaction of sediment stored behind dams can give rise to high uplift pressures which could endanger their safety. The uplift pressures depend upon the permeability and compressibility of both the sediment and the foundation and are controlled by Biot's equation. Uplift pressures are computed for a single dam and foundation with a range of properties. The results show that for the conditions analyzed, the uplift pressures are largely controlled by the foundation permeability with the largest uplift pressures occurring for the highest foundation permeability. The possibility of liquefied sediment flowing into fissures in the foundation rock is also considered and can result in much higher predicted uplift forces. This condition is only likely to occur for a foundation rock of high permeability.

INTRODUCTION

Buildup of sediment behind concrete dams may occur as a natural process, or more recently concrete dams have been designed to retain mine waste material or tailings. In either case, the possibility of earthquake induced liquefaction of these materials should be considered. Such liquefaction could cause increases to both the static and dynamic forces acting on the face of the dam as well as increased uplift pressures on the base of the dam. If the height of sediment behind the dam corresponds to the reservoir full condition, then upon liquefaction, the horizontal static forces on the face of the dam would increase by about 33%. The dynamic horizontal forces on the face of the dam would also increase. However, the uplift forces on the base of the dam or through any section of the dam could possibly increase by a factor of 2. The potential for such large increases in uplift pressure due to liquefaction of sediment could jeopardize the safety of many existing dams.

The magnitude of the increase depends upon the geometry of the dam and its foundations as well as the permeability and stiffness properties of both the liquefied soil and the foundation rock. In addition, the possibility that the liquefied soil could flow through cracks in the rock needs consideration. The purpose of this study is to examine the range of possible uplift pressures for various combinations of soil and rock properties.

DESIGN PROBLEM

Liquefaction assessment of a number of projects carried out on a total stress basis has shown that the sediments stored behind dams may liquefy to their full depth. An effective stress analysis (Finn, Byrne, Martin, 1976 or Finn et al, 1986) generally shows that liquefaction commences near the surface of the sediment and works its way down as the shaking proceeds and may or may not reach the base of the sediment depending on the shaking level and the density of the sediments. It will be assumed herein that the sediment liquefies to its full depth and the concern is for the uplift pressures beneath the dam induced by such liquefaction.

If the dam foundation is of very low permeability compared to the sediment, then fluid will drain upward through the sediment rather than downward and beneath the dam, and there will be little increase in uplift pressure. On the other hand, if the permeability of the rock is much higher than the sediment, the fluid will drain out beneath the dam and the uplift pressures could be quite high.

There is also the possibility that if the foundation rock is fissured the sediments themselves rather than just the water may enter the fissures. Such a situation occurred at the Mufulira Mine in Zambia in 1970 when a half million cubic metres of tailings flowed downward through fissures in the rock and entered the mining area 500 m below.

ANALYSIS PROCEDURE

There is a wide range in possible geometries, sediment and rock properties to consider. In this study just a single geometry has been chosen as shown in Fig. 1. The dam considered is 25 m high and has a base width of 20 m. The pervious rock foundation has a depth of 25 m.

The pertinent properties controlling the uplift pressures are the permeability and compressibility of the sediment and foundation rock. The range of permeabilities and

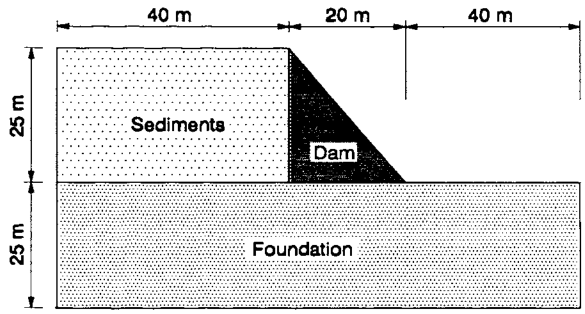

Fig. 1. Geometry of the Dam Analyzed.

compressibilities chosen for the sediments and foundation rock are listed in Table 1.

Table 1. Properties used in the analyses.

Material	Permeability (K) (m/s)	Young's Modulus (E) (kPa)	Coeff. of Consolidation (c_V) (m^2/sec)
Sediment (S)	10^{-4} 10^{-5} 10^{-6}	3,000	2.12 10^{-2} 2.12 10^{-3} 2.12 10^{-4}
Foundation (F)	10^{-5} 10^{-7} 10^{-9}	90,000	6.36 10^{-2} 6.36 10^{-4} 6.36 10^{-6}

The rate of drainage is largely controlled by the coefficient of consolidation, c_V, shown in Table 1, which largely depends on the product of the permeability and the modulus of the sediment or rock, and from Desai and Christian (1977) is given by:

$$c_V = \frac{k \cdot E}{2(1+\nu)(1-2\nu)\gamma_W} \tag{1}$$

where ν = Poisson's ratio, taken as 0.2 for all material.

The range in sediment permeabilities listed in Table 1 are largely based on Mital and Morgenstern (1975). The post-liquefaction modulus of the sediments is based on strain data presented by Tokimatsu and Seed (1987). The permeability of the rock is based on Lancaster-Jones (1968) and its modulus was assumed to correspond to that of a medium dense sand. The fissured rock could be significantly stiffer than this, which would have the effect of raising c_V.

The concrete dam is considered to have zero permeability and acts as a flow boundary. It is assumed in the analysis that complete liquefaction of the sediment is caused by the earthquake, with the result that the pore fluid pressure increases from $h\gamma_W$ to $h\gamma$, where h = the height of the sediment above the point considered and γ_W and γ are the unit weights of the water and soil respectively. The excess porewater pressure generated in the sediment, $u = h(\gamma-\gamma_W)$. These pore pressures are assumed to redistribute and dissipate in accordance with Biot's (1941) theory of consolidation. A finite element solution of the consolidation equation is obtained using the computer program CONOIL-II, Byrne and Srithar (1989). The sediment and rock properties used were listed in Table 1 and the boundary conditions assumed are shown in Fig. 2.

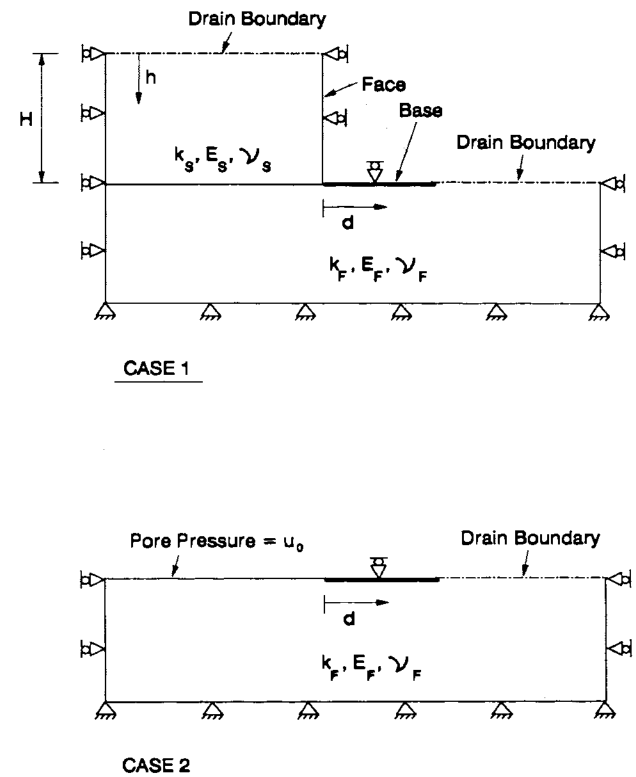

Fig. 2. Boundary Conditions Assumed in the Analyses.

Two boundary conditions were considered.

Case 1: Both the top surface of the sediments as well as the downstream surface of the rock are drainage boundaries with zero pressure head. In this case only the water within the sediment is considered to flow, and the excess porewater pressure generated in the sediments may flow upward to the surface of the sediment or downward into the foundation rock.

Case 2: The upstream surface of the rock has prescribed excess fluid pressure, $u_0 = H(\gamma-\gamma_W)$, where H = the height of sediment about the rock base. The downstream rock surface has zero pressure as before. This is considered to model the case where the liquefied tailings may flow into the rock through a pattern of fissures. It is considered here that the liquefied sediment stays liquid and that the flow through the rock will not significantly lower the height of sediment in the reservoir in the time span considered.

Ranges in values of both permeability and compressibility of the sediment and the foundation rock were used in analyses in accordance with Table 1. These ranges are thought to cover the practical range likely to be encountered.

RESULTS

Case 1 Condition

The predicted excess pore pressure distributions along the base of the dam at varying times after the earthquake are shown in Figs. 3, 4 and 5, for the Case 1 condition. The excess porewater pressures are shown in terms of a pore pressure ratio u/u_0 in which u is the current excess porewater pressure, and u_0 is the maximum excess porewater pressure which occurs at the base of the sediment. $u_0 = H(\gamma-\gamma_W) = 25(7) = 175$ Kpa, for the condition examined.

In all cases the excess pore pressures at the base are initially high only near the upstream face of the dam. Gradually with time, the pressures are transmitted beneath the dam. However, the pressure is also falling at the upstream face due to dissipation. Eventually, the excess pore pressure drops to zero.

The situation for the high value of sediment permeability $k_S = 10^{-4}$ m/sec is shown in Fig. 3. The effect of varying the foundation rock permeability is shown in Figs. 3a, b, and c. These figures show that much higher excess pore pressures occur for the high permeability rock (Fig. 3a) as opposed to Figs. 3b and c. For the low permeability foundation rock, the water from the sediments drains upward to the surface rather than downward through the rock, which results in much lower excess porewater pressures beneath the dam.

The effect of lower sediment permeabilities is shown in Figs. 4 and 5. It may be seen that even for a sediment permeability $k_S = 10^{-6}$ cm/sec, the low permeability rock is still effective in controlling the advance of excess porewater pressures in the foundation, and the water mainly drains to the surface of the sediment rather than beneath the dam.

Figures 3, 4 and 5 basically show that it is important to have the permeability of the foundation rock low compared to that of the sediment. In practice, a cut-off through the rock close to the dam would be used together with a drainage system. This should have the effect of reducing the uplift pressures in the drainage zone downstream of the cut-off. The uplift pressure upstream of the cut-off may be increased.

From a stability point of view it is the total uplift force beneath the dam that is of concern. The total uplift force at the

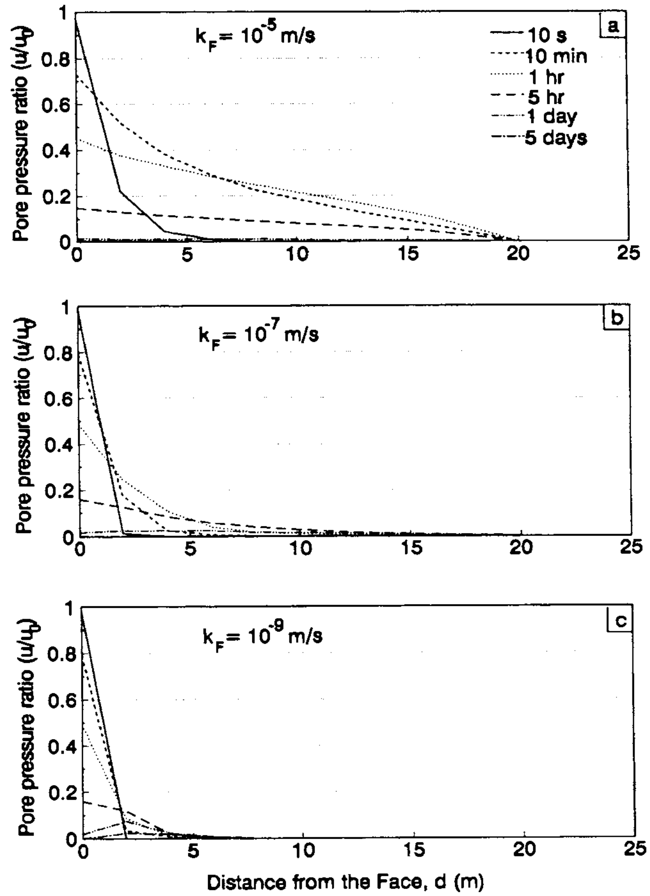

Fig. 3. Excess pore pressure ratio beneath the base of the dam for $k_S = 10^{-4}$ m/s.

various times and for the various combinations of sediment and foundation permeability are shown in Fig. 6.

The excess uplift forces beneath the base of the dam for the various conditions were computed from the uplift diagram of Figs. 3, 4 and 5. These uplift forces vary with time and are shown in dimensionless form in terms of an uplift force ratio vs. time. The uplift force ratio is the ratio of the excess uplift force beneath the dam to the steady state uplift force, defined as the maximum excess pore pressure, u_0, multiplied by 1/2 the base length. Thus for the dam analyzed an uplift force ratio = 1 corresponds to a force of 1/2 (20)(175) = 1750 kN.

The conditions for the high permeability sediment $k_S = 10^{-4}$ m/sec is shown in Fig. 6a. It indicates that the highest excess uplift forces occur for the highest foundation rock permeability, $k_F = 10^{-5}$ m/sec. The uplift force ratio increases with time to a maximum value of 0.4 which occurs about 10 minutes after the earthquake. Thereafter the uplift

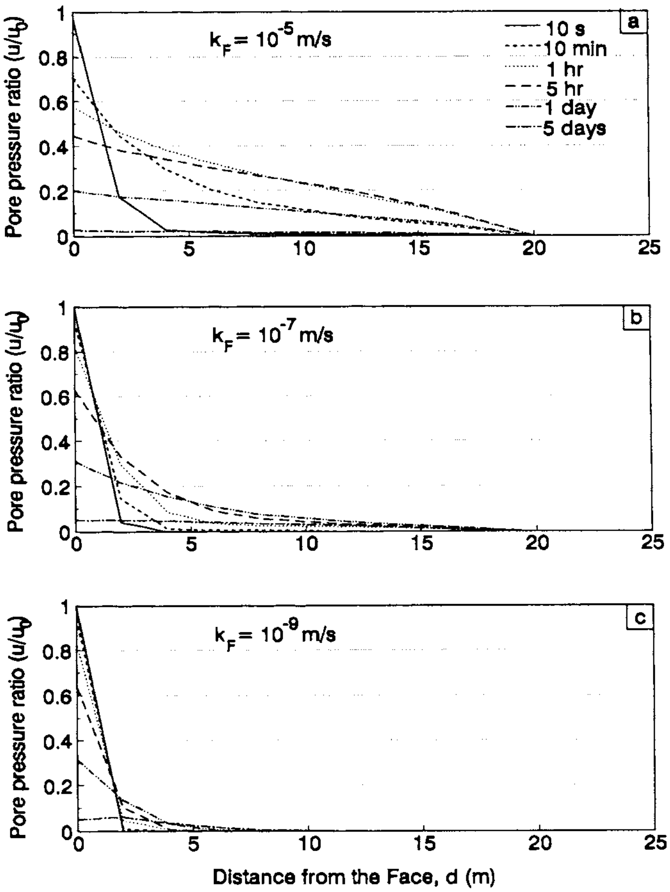

Fig. 4. Excess pore pressure ratio beneath the base of the dam for $k_S = 10^{-5}$ m/s.

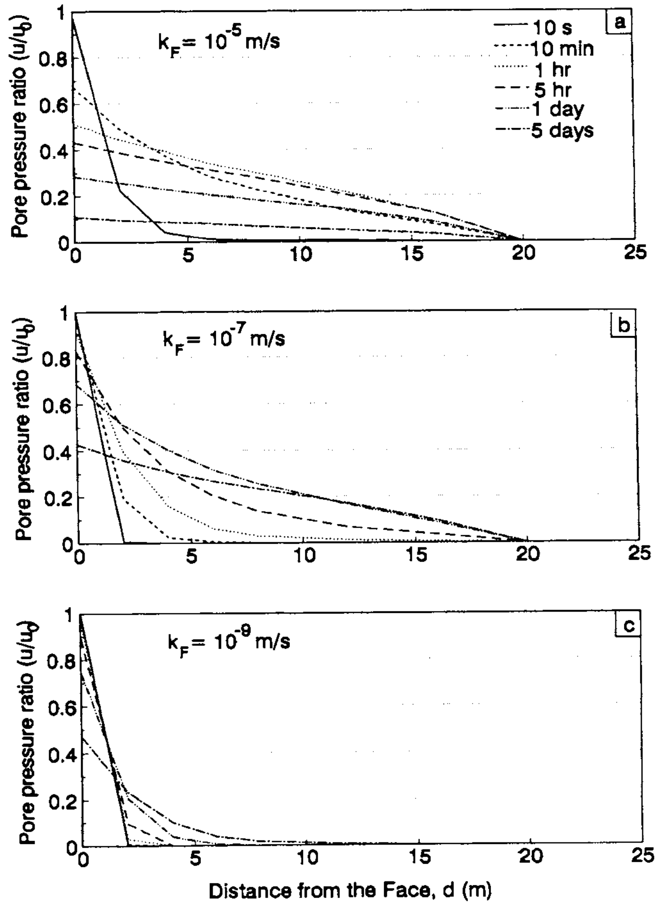

Fig. 5. Excess pore pressure ratio beneath the base of the dam for $k_S = 10^{-6}$ m/s.

forces drop and are essentialy zero after about 1 day.

The condition for the intermediate sediment permeability, $k_S = 10^{-5}$ m/sec is shown in Fig. 6b. The trend of higher uplift forces with the higher foundation permeability again occurs. The maximum uplift force ratio is again about 0.4 and occurs after abour 1 hour, reducing to near zero after about 5 days.

The conditions for the lowest sediment permeability $k_S = 10^{-6}$ m/sec is shown in Fig. 6c. The maximum uplift force ratio is again 0.4 but this time it can occur with the foundation rock permeability, $k_F = 10^{-7}$ or 10^{-9} cm/sec. With $k_F = 10^{-7}$ m/sec, the peak uplift ratio occurs after a time of about 1 hour whereas with $k_F = 10^{-9}$ m/sec the peak uplift force occurs after about 1 day and significant uplift forces remain after 5 days.

These results show that for the range considered, the highest uplift pressures occur for the highest foundation rock permeability regardless of the sediment permeability. For the high foundation rock permeability, the peak uplift pressure ratio is about 0.4, and the sediment permeability only effects the time at which the peak occurs; longer for lower values of k_S.

Case 2 Condition

The predicted excess pore pressure ratios beneath the base for the case 2 conditions in which full liquefaction pressures are assumed to be maintained at the upstream rock surface are shown in Fig. 7. For this assumption only the permeability of the foundation rock is pertinent as it is assumed that the sediments themselves flow as a liquid into the fissured rock. The results for $k_F = 10^{-5}$, 10^{-7} and 10^{-9} m/sec are shown in Figs. 7a, b, and c, respectively and indicate that for all cases the pore pressures will build up to the steady state condition with time as expected. For the high $k_F = 10^{-5}$ m/sec, the steady state condition is reached in about 1 day, and thereafter there is no further build up.

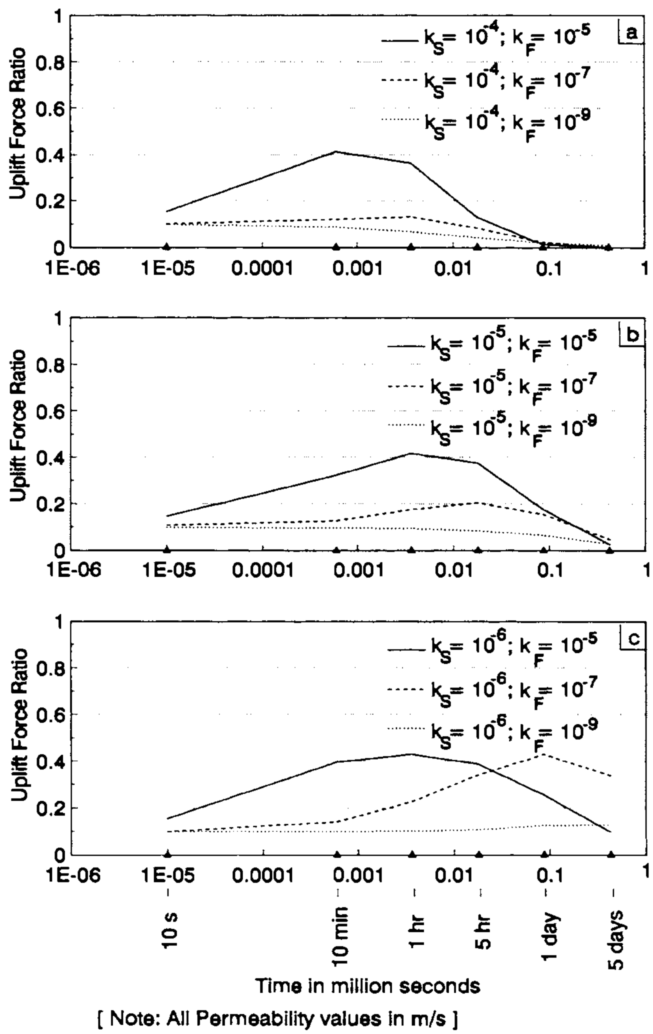

Fig. 6. Total uplift force ratio beneath the dam for Case 1.

For $k_F = 10^{-7}$ m/sec, the steady state is predicted to occur after 20 days and for $k_F = 10^{-9}$ m/sec, the steady state has not been reached in 20 days. As expected therefore the uplift pressures build up more slowly for the lower k_F condition.

The uplift force ratios implied by these pressures as a function of time are shown in Fig. 8. It may be seen that for all cases the uplift forces continue to rise with time reaching a maximum value of 100% of the maximum possible or steady state value. The permeability of the foundation controls the rate of buildup of these forces. For $k_F = 10^{-5}$ m/sec the steady state conditions occurs about 5 hours after the earthquake. For $k_F = 10^{-7}$ m/sec, the steady state is reached after about 20 days while for $k_F = 10^{-9}$ m/sec the uplift force is about .35 of the steady state value after 20 days and would be predicted to continue to rise.

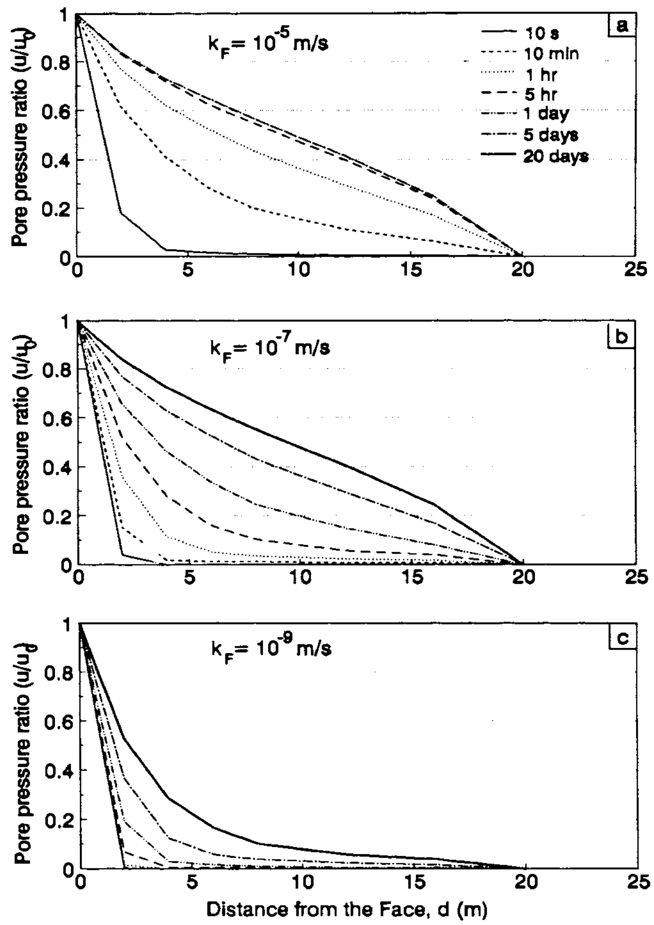

Fig. 7. Excess pore pressure ratio beneath the base of the dam for Case 2.

These high values of predicted uplift force are likely unrealistic, especially for the low k_F values because the sediments would solidify by drainage to the surface as considered in Case 1. The results shown in Fig. 5c indicate that even for the lowest $k_S = 10^{-6}$ m/sec, the excess pore pressure ratio at the upstream toe of the dam would have dropped to 0.5 in 5 days. Thus the assumption that the pressure ratio stays equal to 1 at the sediment-rock contact is overly conservative for both the $k_F = 10^{-7}$ and 10^{-9} m/sec conditions. The predictions for the Case 1 condition are likely more realistic for $k_F < 10^{-7}$ m/sec, with a maximum uplift force of about 40% of the steady state conditions. For the high permeability rock conditions $k_F = 10^{-5}$ m/sec, it is possible that the steady state uplift force condition could develop.

DISCUSSION OF RESULTS

The analyses carried out indicate that a high permeability sediment together with a low permeability rock foundation gives the lowest uplift pressures in the event of liquefaction

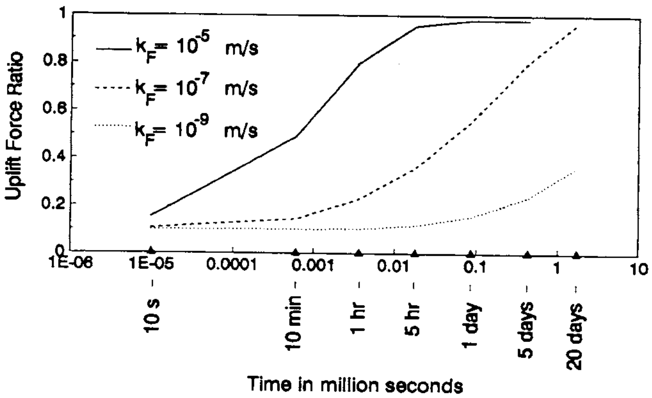

Fig. 8. Total uplift force ratio beneath the dam for Case 2.

of the sediments. For this condition the excess pore water pressures essentially dissipated by drainage to the surface of the sediments, and there is insufficient time for the pressures to propagate into the foundation rock beneath the dam.

Conversely if the foundation permeability is high, water from the liquefied sediment can quickly propagate beneath the dam and lead to high uplift pressures. The results indicate that the foundation permeability largely controls the peak uplift force, while the sediment permeability controls the time after the earthquake at which the peak occurs.

If it is considered that the sediments themselves can flow as a liquid into fissures in the rock, then much higher uplift pressures could occur if the sediment remains in a liquid state. However, if the permeability of the rock is low, then it takes considerable time for the pressure from the liquid sediment to propagate beneath the dam and during that time solidification of the sediments would occur. This would cause the fluid pressure at the base of the sediment to drop and the flow conditions beneath the dam would be governed more by Condition 1.

The rate of pore pressure dissipation is largely controlled by the product of the permeability and the modulus of the material. The stiffness of the fissured rock could well be 10 to 100 times stiffer than chosen and this would have the same effect as increasing the foundation permeability by these amounts. Such an increase would result in higher predicted uplift pressures.

The case study examined here is based on the assumption that the sediments will liquefy to their full depth. As discussed earlier in this paper, effective stress dynamic analyses of the pore pressure generation process indicate that for sediments of uniform density with the water table at the surface, liquefaction commences near the surface and progresses downward.

For many cases, complete liquefaction of the sediments may not occur, and an effective stress analyses can be used to give the excess pore pressure distribution with depth in the sediment at the end of the earthquake shaking period. These excess pore pressures are then used in CONOIL-II, and because they will be lower than previously assumed, they may lead to significantly lower uplift pressures. In addition, if liquefaction does not extend to the base of the sediments, flow of the sediments themselves into the fissured rock is unlikely.

A low permeability layer of nonliquefiable material at the base of the sediments would significantly reduce the possibility of high excess uplift pressures beneath the dam.

SUMMARY

Earthquake induced liquefaction of sediments stored behind dams can give rise to severe uplift pressures that could affect the stability of the dam. The uplift pressures depend upon the permeability and the compressibility of both the sediment and the foundation. The propagation and dissipation of such pressures are governed by Biot's equation.

Uplift pressures were computed for a single dam and foundation having a wide range of properties. Biot's equation was solved for these conditions using a finite element procedure.

The results are shown in the form of uplift pressure diagrams at various times after the earthquake, and indicate that the most severe uplift conditions arise when the permeability of the foundation is high. For the geometry consider the uplift force could be as high as 40% of the steady state value and would occur from 10 minutes to 1 day after the earthquake depending on the permeability of the sediment. For the case considered, the permeability of the foundation rock controlled the value of the uplift force, while the permeability of the sediment controlled the time taken to reach the maximum uplift value.

Analyses were also carried out for the assumption that the sediment itself could flow into fissures in the rock. The results indicate that much higher uplift pressures could occur for this case, provided the sediments remained in a liquid state. If the rock permeability is high, the steady state condition is reached in a matter of hours and would imply very high uplift forces or the dam. Because the sediments could very well remain liquid for this length of time, such a situation is possible. If the rock permeability is low, then the full steady state uplift condition would take many days to occur and it is likely that solidification of sedimentation would take place and prevent their further movement into the foundation rock and thus curtail the uplift forces.

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