EFFECT OF ASYNCHRONOUS INPUT ON THE RESPONSE OF DAMS

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SUMMARY

The effect of an earthquake on a structure depends on its speed of propagation relative to the size of the structure. If the speed is low or the structure is large, a satisfactory analysis must take into account the finite travel time of the earthquake across the foundation of the structure. This paper gives a parametric study on the dynamic response of an embankment dam subjected to asynchronous input motion with varying travelling velocities. Similar study also conducted on an arch dam with differing support motions.

INTRODUCTION

The speed of propagation of earthquakes through foundations varies considerably. In the soft clays of the North Sea, on which some platforms are founded, it might be as little as 200m/s for the shear-wave, rising in good rock to something in the region of 4000m/s. For large structures the earthquake takes a finite time to travel from one side to the other, and it is then not satisfactory to employ the standard approach of earthquake engineering, in which the whole region of contact with the foundations is subjected to the same acceleration simultaneously. Instead, the finite travel time must be taken into account, and its effect is to produce what are called pseudo-static displacements, in addition to the normal dynamic displacements. Whereas the latter are caused by inertia, the former are caused by the differential movement of the structure-foundation interface, and their determination require the deformed shapes of the structure to be calculated for given unit displacements of the degrees of freedom with which the structure is connected to the foundation [1]. The computational problem is therefore appreciably greater than in the conventional seismic analysis, where all points have the same acceleration.

These additional, pseudo-static, displacements are time-dependent, and cause stresses to be added to the dynamic stresses which derive from inertia. The magnitude of these stresses is considered first in this paper for an embankment dam, across the base of which the S16E component of the San Fernando (1971) earthquake travels at infinite speed, at 4000m/s, and then at 2000m/s. In the first calculations the earthquake acceleration is in the horizontal direction; afterwards it is multiplied by two-thirds and caused to be effective in the vertical direction but still travelling horizontally. The infinite speed does, of course, give the conventional result, and this is very useful in checking the proper working of the computer programme which has been written for incorporation in SAP IV [2].

The second series of calculations have been performed on an arch dam, the Victoria dam now under contruction in Sri Lanka. Here a comparison has been made between stresses produced when the whole base is subjected to the S16E component of San Fernando in the upstream-downstream direction,

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against when only the left-hand half of the base is so subjected.

EQUATIONS OF MOTION

The finite element method is used, so that the system is represented by a finite number of degrees of freedom. These are divided into two categories. First, those which belong to node points which connect the structure to the ground; these are referred to as ground degrees of freedom, GDOF, and each one can experience a separate, but specified, transient acceleration. Second, the remaining degrees of freedom, called response degrees of freedom, RDOF.

The statement of dynamic equilibruim requires that inertia, damping and stiffness forces sum to zero, which, in the usual rotation and partitioning into GDOF and RDOF leads to[3].

$$\begin{bmatrix} M & M_g \\ M_g{}^T & M_{gg} \end{bmatrix} \begin{Bmatrix} \ddot{\nu}^t \\ \ddot{\nu}_g \end{Bmatrix} + \begin{bmatrix} C & C_g \\ C_g{}^T & C_{gg} \end{bmatrix} \begin{Bmatrix} \dot{\nu}^t \\ \dot{\nu}_g \end{Bmatrix} + \begin{bmatrix} K & K_g \\ K_g{}^T & K_{gg} \end{bmatrix} \begin{Bmatrix} \nu^t \\ \nu_g \end{Bmatrix} = 0 \quad (1)$$

Here, lower case t denotes total displacement. This definition is necessary because for asynchronous ground input the normal dynamic displacement, ν, due to inertia, is argmented by a displacement, called the pseudo-static displacement, ν^s, which is produced by the differential ground movement, and would be present even if the structure had no mass. If fact,

$$\nu^t = \nu + \nu^s \quad (2)$$

Considering first a single GDOF, ν_{gi}, the displacement which it causes in all RDOF can be written

$$\nu^s = r\,\nu_{gi} \quad (3)$$

where r is called the ground-displacement shape vector. If describes the values of the RDOF when ν_{gi} is given unit value. It is not time-dependent. If (3) and (2) are used in (1), it is found that

$$M\ddot{\nu} + C\dot{\nu} + K\nu = -(Mr + M_g)\,\ddot{\nu}_{gi} - (Cr + C_g)\,\dot{\nu}_{gi} - (Kr + K_g)\,\nu_{gi} \quad (4)$$

and since the equation of static equilibruim must be contained within (4), its last term is zero. This leads to the definition of r as equal to $-K^{-1}Kg$. If damping is assumed proportional, and if a diagonal mass matrix is used, there remains

$$M\ddot{\nu} + C\dot{\nu} + K\nu = -Mr\ddot{\nu}_{gi} \quad (5)$$

An r-vector has to be calculated for each GDOF, and if these are compiled into an R matrix,(5) becomes

$$M\ddot{\nu} + C\dot{\nu} + K\nu = -MR\ddot{\nu}_g \quad (6)$$

where $\ddot{\nu}_g$ is the vector of ground accelerations of the GDOF. Although r was defined above, experience indicates that the best way to calculate it for each GDOF is to add to the structure stiffness matrix a very large stiffness corresponding to the GDOF, and to apply to the structure a corresponding load of the same size. The GDOF then has a displacement which is close to unity, and other displacements form the r-vector.

CALCULATION OF STRESSES

The dynamic displacements are calculated from (6) either by the model method or by direct integration. For the results given here the former was used, employing five modes. To obtain total displacement, ν^s must be found, and this comes from (3) with the ground displacement obtained by double integration of given ground acceleration. Care must be exercised here to ensure that the true residual displacement (usually zero) is achieved. The total displacement is now obtained from (2), after which stresses are obtained. The computer programme developed for this work retains only the maximum values of each component in displacement and stress vectors.

AN EMBANKMENT DAM

The cross-section chosen for the assessment of the effect of the travelling wave is shown in Fig. 1. The dam is 64.8 m high, with a base length of 410.7 m, and its properties, together with those of the fill and core are given in Fig. 1. The continuous contact between the foundation block and the surrounding soil is represented by a finite number of GDOF. For a dam this number is large, and to bring the computational task within reasonable bounds, the base has been divided into 4 regions, so that only 4 different r-vectors are required. In Fig. 1 the stresses σ_{yy}, σ_{zz} and σ_{zy} across section I are presented for the three speeds, ∞, 4000m/s and 2000m/s, of the horizontally propagating S16E San Fernando signal; the acceleration is horizontal. It is seen that the σ_{yy} and σ_{zz} stresses increase appreciably as the speed decreases.

Fig. 2 gives similar results for a signal which has two thirds of the intensity of the previous signal, propagating longitudinally, but with an acceleration in the vertical direction. The three speeds produce less difference in stress magnitude, but it is important to note that the general magnitude of stresses is of the same order as for horizontal acceleration.

VICTORIA ARCH DAM

This 110 m high dam is currently under construction in Sri Lanka. Its crest-length is 528 m and the 3D finite element mesh for dam and foundation is given in Fig. 3. There are 108, 20-node thick-shell elements in the dam, and 114, 8-node 3D elements in the foundation, giving 2694 degrees of freedom. To assess the effect of asynchronous motion in this case, a comparison has been made between the S16E San Fernando signal attacking the whole of the base of the foundation simultaneously, and attacking only the whole of its left-hand half, with the right-hand held fixed. In both cases the horizontal acceleration is upstream-downstream

A complete digital map of stresses was obtained, but space precludes their presentation here. Instead, crown cantilever stresses on the downstream face are given in Fig. 4, for the two conditions studied. It is seen that the pattern of stress differs appreciably between the two cases, with the important hoop-stress (σ_{xx}) having less variation from base to crown in the multiple-support case.

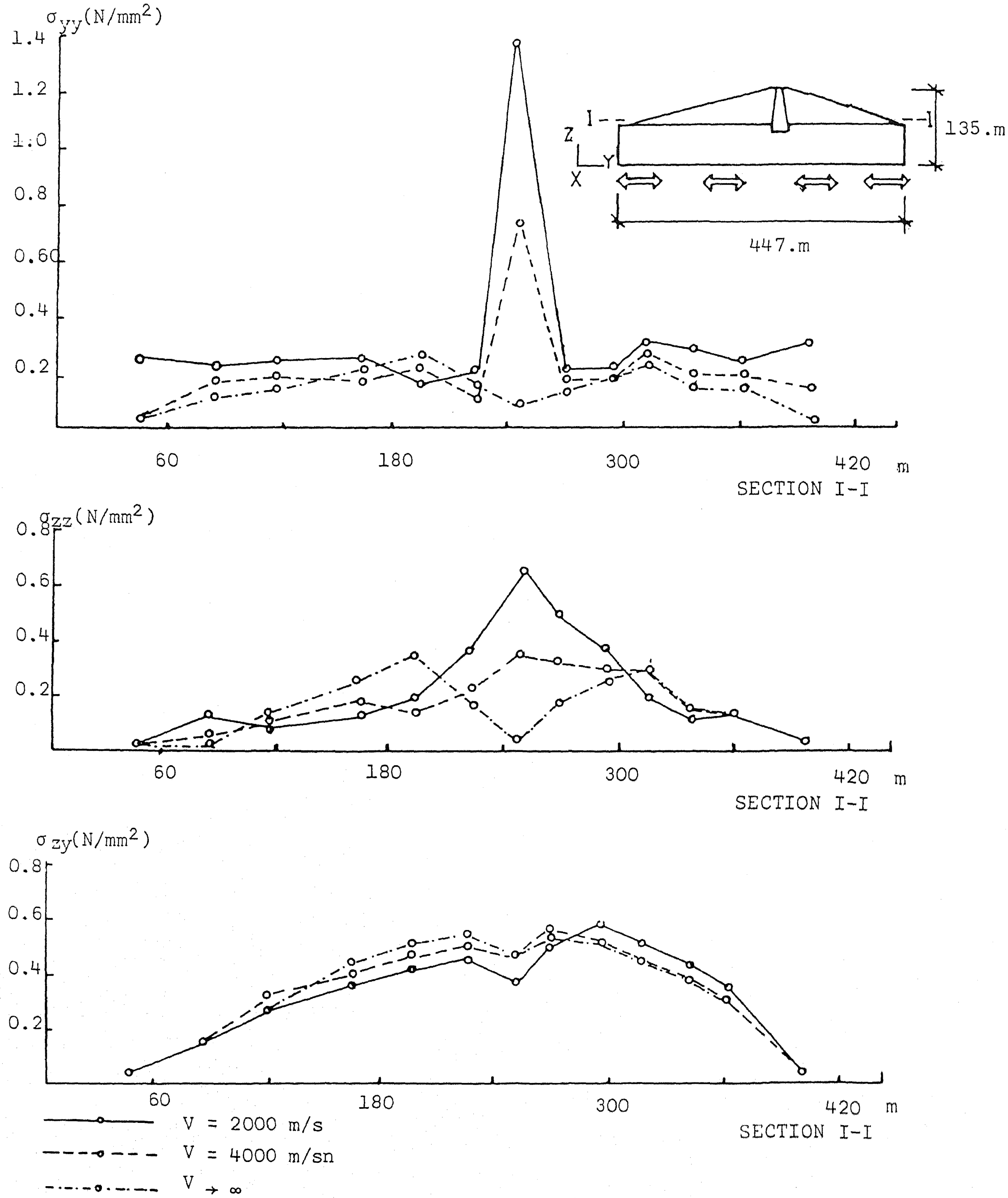

FIG 1. STRESSES IN THE EMBANKMENT DAM DUE TO LATERAL MOTIONS

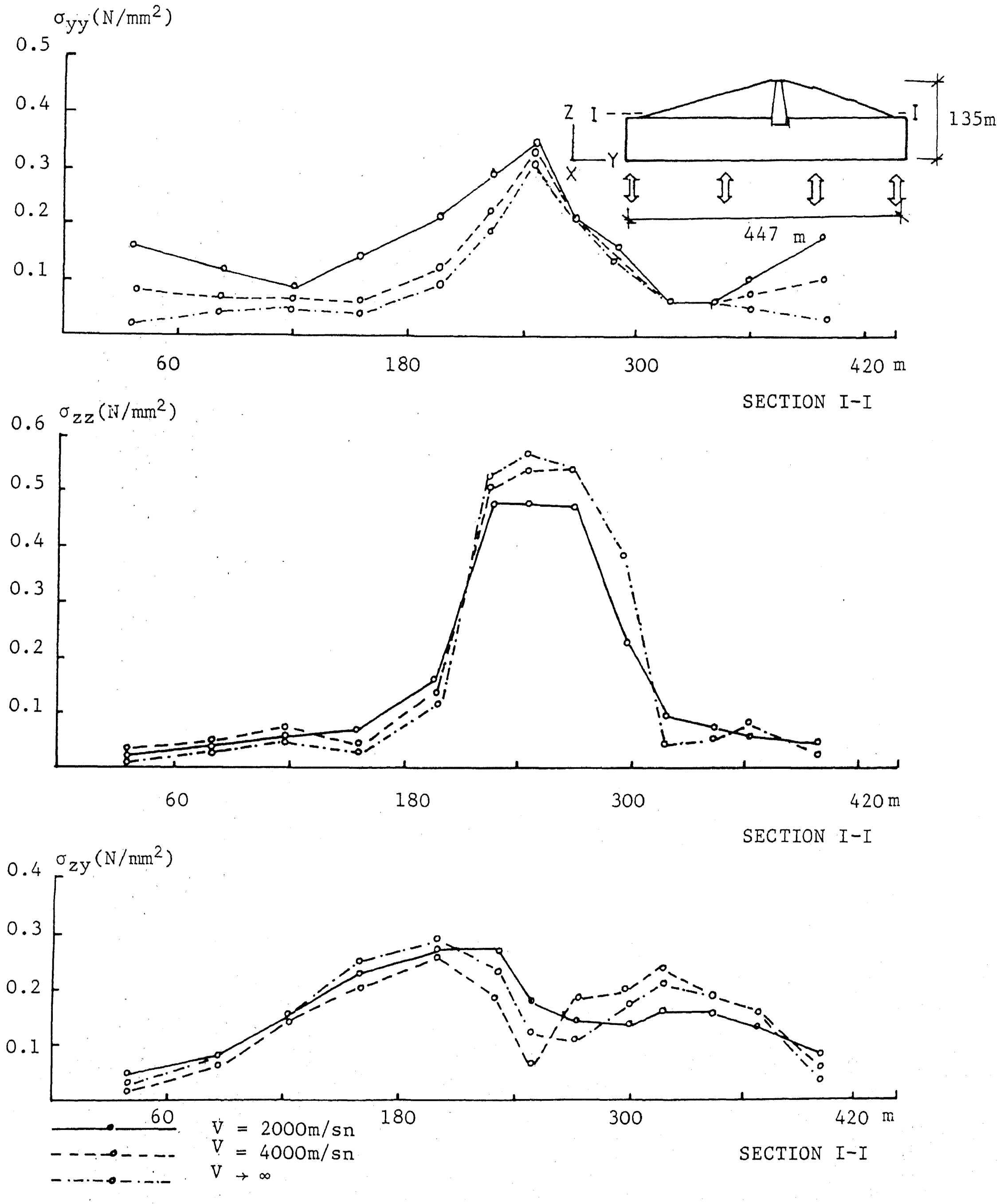

FIG. 2 STRESS IN THE EMBANKMENT DAM DUE TO VERTICAL MOTIONS

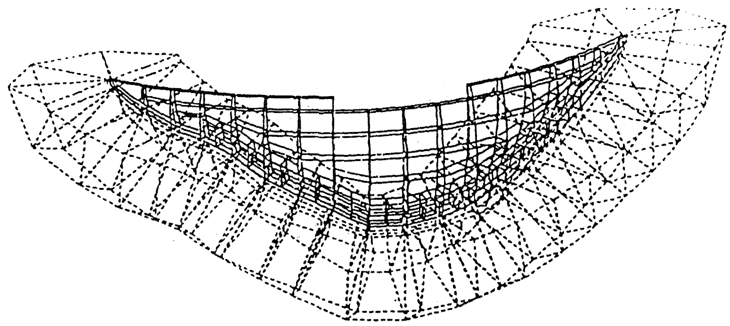

FIG 3. AN AXONOMETRIC VIEW OF VICTORIA DAM MESH

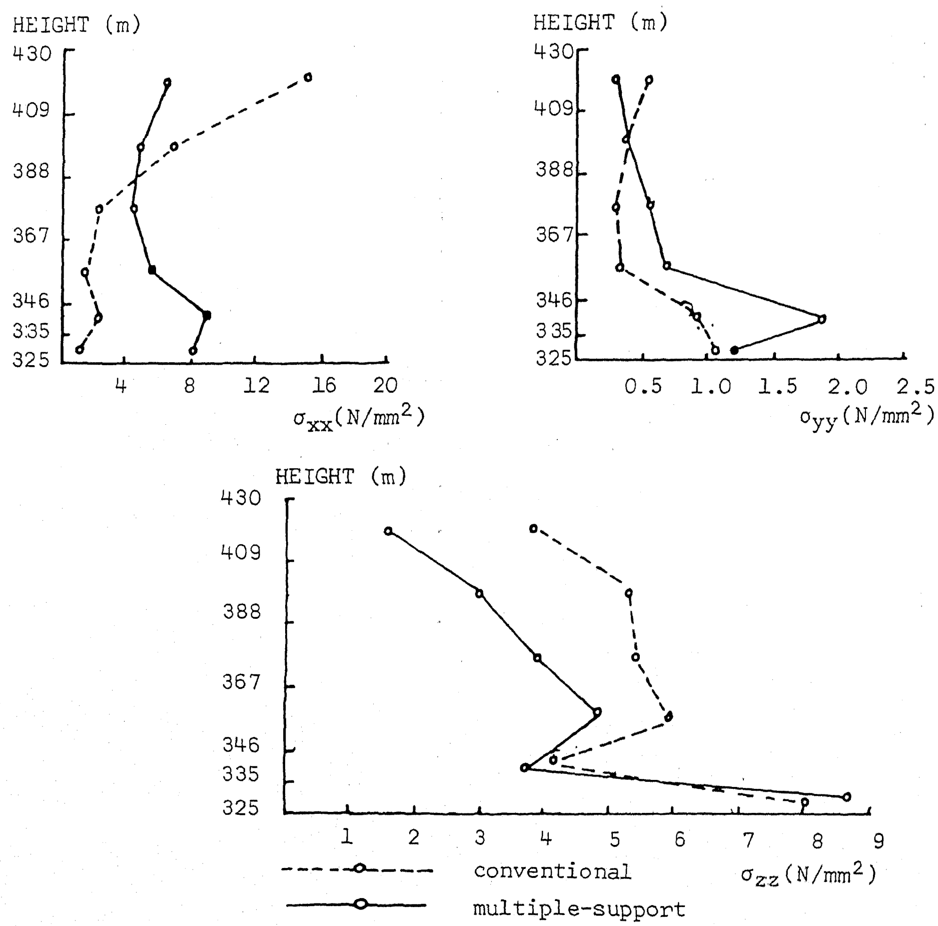

FIG 4. STRESSES ON THE DOWNSTREAM FACE OF VICTORIA DAM

CONCLUSIONS

Asynchronous input with varying wave velocities and multiple-support base excitations both have the same approach in the solution. The basic difference between common base acceleration and the above is that the latter requires the calculation of pseudo-static responses which will be added to the dynamic responses. On the evidence of results presented, it is seen that pseudo-static stresses are significant in magnitude for varying velocities and should be taken into account in the design.

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