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NONLINEAR DYNAMIC BEHAVIOUR OF SATURATED SANDY SOIL INCLUDING LIQUEFACTION

D.K.PAUL[1], A.H.C. CHAN[2] and O.C ZIENKIEWICZ[2]

1 Department of Earthquake Engg., Univ. of Roorkee, Roorkee, India.
2 Department of Civil Engg., Univ. College of Swansea, Swansea, U.K.

SUMMARY

A powerful analysis method to evaluate the total (transient and consolidation) response of liquefiable soils taking into account the complete interaction of the non-linear soil and the entrapped fluid has been developed using a stabilised implicit-implicit staggered time integration scheme in an incremental-iterative form. The numerical results thus obtained are compared with the experimental response of excess pore pressures and settlement which was carried out at Cambridge Geotechnical Centrifuge.

INTRODUCTION

Liquefaction of ground is associated with large permanent displacement resulting in substantial forces on structures which may lead to major damage of structures during a seismic activity. Large scale damage to important structures resting on saturated soil have been observed during major earthquakes specially the Niigata earthquake, Japan (1964), the San Fernando earthquake, USA (1971), the Chilian earthquake and the Nihonkai Chubu earthquake, Japan (1983). On several occasion, it is observed that failure to earth structures due to liquefaction occurred some time after an earthquake (Akiba(1941) and Seed(1979)). The flow slide of San Fernando dam occurred about 1 minute after the end of earthquake shaking of 1971. The failure of Mochi-Koshi tailing dam (Japan) occurred 24 hrs after the Izu-Oshima earthquake of 1979 (Ishihara(1984)). It is of interest, therefore, to study the post earthquake behaviour of earth structures. Following general observations are made during the liquefaction of ground, (i) settlement or densification, (ii) rise of pore water pressure, (iii) liquefaction or fluidisation, (iv) rise of pore water pressure after the excitation, (v) sedimentation or settlement of suspended soil particles and (vi) consolidation.

The two phase coupled water-solid skeleton formulation of Biot (extended by Zienkiewicz) has been adopted for saturated sandy soil. In this formulation the problem lies between the two extremes of an "undrained" and "drained" response since the flow of fluid takes place depending upon the permeability of the medium. The soil is represented by Pastor-Zienkiewicz generalised plasticity soil model. The numerical solution of such a problem involves discretisation of both the spatial and temporal domains. To obtain the long term response which include both fast transient process and slow consolidation process a stabilised staggered implicit-implicit time integration scheme with a variable time step is developed and used in the analysis. The experimental results obtained at Cambridge Geotechnical Centrifuge on a flat sand bed are numerically simulated and the results compared.

MODELING OF LIQUEFACTION

The densification of sand as well as the dynamic interaction between the pore fluid and soil are attributed to the main cause of liquefaction. This largely depend on the nonlinear modeling of sand behaviour. The saturated sand behaviour depends on the effective stress. Martin, Finn and Seed(1975) presented a pseudo static approach while Zienkiewicz and Bettess(1980) and Ishihara and Towhata (1982) used two phase soil-pore fluid dynamic interaction in which some simplified assumption have been made with respect to constitutive model of sand and the mode of pore pressure generation. In this analysis, the saturated soil is treated as two phase media consisting of the pore fluid and the soil skeleton. In the finite element analysis, the u-p formulation is adopted. The analysis considers the drainage during the whole process. To identify the liquefaction, the primary goal is to identify the state for reaching the effective stress $\underline{\sigma}' = 0$ condition in the soil profile, thereby triggering the development of liquefaction effects at the ground surface.

PORE-FLUID SOIL INTERACTION

Two types of analyses are usually carried out for saturated soil, (a) total stress analysis and (b) effective stress analysis. In the total stress analysis, the material is modeled as one phase equivalent solid and the interaction effects are neglected. In the effective stress analysis, the saturated soil is considered as two phase media where the pore pressure effect and its interaction with soil skeleton are included. The solution based on coupled soil-pore fluid and generalised incremental form was derived by Zienkiewicz et al. (1980). In which large strain and nonlinear material behaviour are included. The derivation of the governing equations can be found in Zienkiewicz and Shiomi (1984).

An approximate formulation is used where the relative acceleration term is dropped. The approximation results into pore pressure and soil skeleton displacement as field variables which is a convenient form. This approximate formulation is due to Zienkiewicz (1978). The resulting coupled differential equations in soil skeleton displacement and pore fluid pressure after the finite element discretisation yield.

$$\underline{M}\,\ddot{\underline{u}} + \underline{C}\,\dot{\underline{u}} + \int \underline{B}^T \underline{\sigma}'' d\Omega = \underline{f}_u + \underline{Qp} \quad (1)$$

$$\underline{S}\,\dot{\underline{p}} + \underline{H}\,\underline{p} = \underline{f}_p - \underline{Q}^T \dot{\underline{u}} \quad (2)$$

Where, $\underline{u}$ are the displacements of the soil and $\underline{p}$ are the pore pressure, $\underline{M}$, $\underline{C}$ and $\underline{B}$ are the mass, damping and the strain-displacement matrices of the soil skeleton, $\underline{S}$ and $\underline{H}$ are the compressibility and the permeability matrices, $\underline{f}_u$ and $\underline{f}_p$ are the forces acting on soil skeleton and the pore fluid, $\underline{Q}$ is the coupling matrix and $\underline{\sigma}''$ are the effective stresses. These matrices can be found in Zienkiewicz et. al. (1978, 1980,1984).

Incidently in such a formulation, the seepage, static (drained/undrained), consolidation and dynamic (structure-soil-pore fluid interaction) analysis can be made in the same frame work.

SOLUTION SCHEME

The solution of the above coupled equations can be carried out in either of the two ways, (i) direct coupled solution, or (ii) partitioned or staggered approach. In partitioned or staggered solution approach, the equations (1) and (2) are solved in a staggered fashion. Although, the analysis is unconditionally stable when applied to individual field but the staggered solution for the coupled system is found to be conditionally stable. A unconditional stable implicit-implicit staggered approach has been developed where a simple modification of (1) is made for this and the stability analysis can be found in Zienkiewicz et.al. (1987). Following advantages are obtained for stabilised staggered solution over the direct coupled solution, (i) the matrices are small as compared to direct coupled solution, (ii) the matrics are symmetric, (iii) the band width is small, (iv) the storage requirement is small, (v) the number of zero's stored are very small within the bandwidth, (vi) the computer operations are small and (vii) the computer implimentation is very simple.

NONLINEARITIES

The basic nonlinearities are due to soil behaviour and the change in permeability, porosity and bulk density. Several soil models are capable of representing the nonlinear behaviour. The nonlinear stress-strain relation for soil is obtained from the model and then the internal nodal forces are obtained. The Pastor-Zienkiewicz (1986) soil model is based on generalised plasticity. The model is very simple as no yield, bounding or plastic potential surfaces are used. It takes into account the plastic deformation during unloading and loading. This soil model is found to be capable of reproducing with reasonable accuracy the behaviour of sands under various loading conditions. It is also capable of reproducing most of the standard triaxial tests. This requires small number of soil parameters to describe the model and therefore, in this investigation P-Z soil model is used.

When a soil is compressed or vibrated, the volume occupied by solid constitutents remain practically unchanged but the volume of voids changes. As a consequence, the permeability, porosity and bulk unit weight of the soil also changes. The permeability matrix depends on the void ratio which in turn depends on the current displacement. The nonlinear analysis is carried out in an iterative-incremental procedure where the tangent stiffness and permeability matrices are used at the beginning of each step.

SPECIAL TREATMENT

Following special treatments are made so that the solution can be obtained cheaply, (i) the u-p formulation, (ii) staggered solution, (iii) lower order of finite element, (iv) lower order integration (v) anti hourglass treatment, (vi) initial stiffness method, and the (vii) variable time step.

If lower order finite elements together with low order integration is used then the calculation can be performed cheaply. Unfortunately, due to hourglass mode the solution becomes unstable and solution breaks down. Formulation of a stable four noded element which is free from hourglass or zero energy modes is used as described in Reference Flangan and Belytschko (1981).

VALIDATION

The analytical validation is discussed by Simon, Zienkiewicz and Paul (1984). Here, the numerical prediction using the above formulation are compared with the Centrifuge experimental results.

Experiment The tests were performed by Venter (1985) at the Cambridge University Geotechnical Centrifuge where a water retaining dyke resting on saturated flat sand bed is subjected to 78g centrifugal force together with the sinusoidal base excitation. The experimental set up of the model is shown in Fig.1.

Finite Element Analysis The plane strain finite element analysis of dyke and saturated flat bed system has been carried out. In this analysis both the soil skeleton and the fluid are mapped by 4-noded isoparametric elements. The mesh consists of 105 soil elements and 105 fluid elements whereas concrete dyke is modeled as rigid block. The mesh is similar to the mesh used by the DIANA project team in Japan. The various other data used in the analysis can be found in Paul and Zienkiewicz (1987). The base excitation is also shown in Fig. 1.

RESULTS AND DISCUSSIONS

Triaxial tests were also carried out to estimate the soil model parameters used in the constitutive modeling of soil. The initial stresses required for the nonlinear dynamic analysis are obtained by the static analysis for the gravitational and the centrifugal forces, and the pressures caused by the reservoir fluid.

A comparision of dynamic response (experimental vs numerical results) of the model including the post earthquake rise and dissipation of excess pore pressure (consolidation) is shown in Fig.2. The excess pore pressure response shows remarkable agreement with the experimental results except the dissipation of pore pressure after the earthquake excitation is slower than the experimental results. This may be the result of considering constant permeability throughout the analysis. It is expected that during violent shaking the permeability may change.

All the pore pressure transducers on the left and the right side of the dyke show similar trend of response and compare very well with the magnitude of peak pressure. All of these show sudden rise of excess pore pressure at the initial stages and attaining peak pressure during the excitation itself then dissipation starts immediately after the earthquake ceases. All the transducers which lie under the dyke show similar trend of response. It is observed that the experimental as well as numerical result show that the excess pore pressures are well below the liquefaction level during excitation but the pore pressure rises to its peak after the earthquake excitation ceases but does not lead to liquefaction state. This rise of pore pressure after the earthquake excitation is responsible for the failure of some of the earth structures.

Figure 2 also shows the response of settlement of the dyke which shows excellent agreement between the experiment and numerical results. It is observed that a significant percentage of settlement takes place even after the earthquake motion ceases.

CONCLUSIONS

The numerical and the experimental results show good agreement during and after the excitation. The P-Z soil model, u-p formulation and the solution procedure are capable of predicting the settlement or densification, rise of pore water pressure, liquefaction or fluidisation, rise of pore water pressure after the excitation, sedimentation and the consolidation. The total response (static/transient/consolidation) is obtained in one algorithm. The partitioned or staggered solution using the variable time step stabilised implicit-implicit time integration scheme is found to be very suitable for such problems. The investigation shows that the variation of permeability takes places during excitation and research effort should be directed to obtained this variation for use in numerical simulation.

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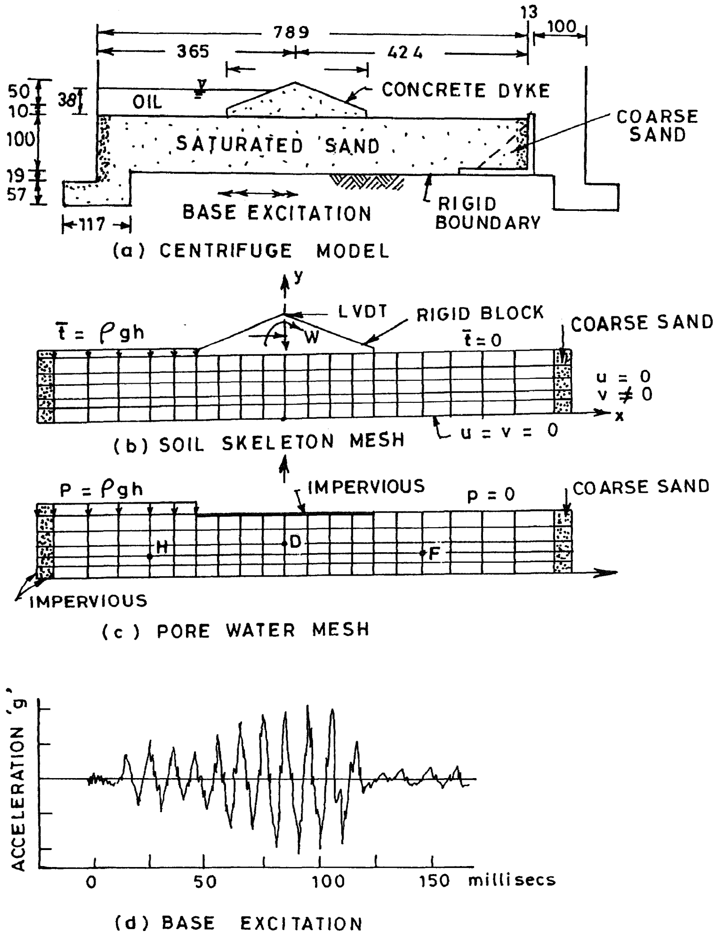

FIG.1_CENTRIFUGE MODEL, FINITE ELEMENT MESH AND BASE EXCITATION

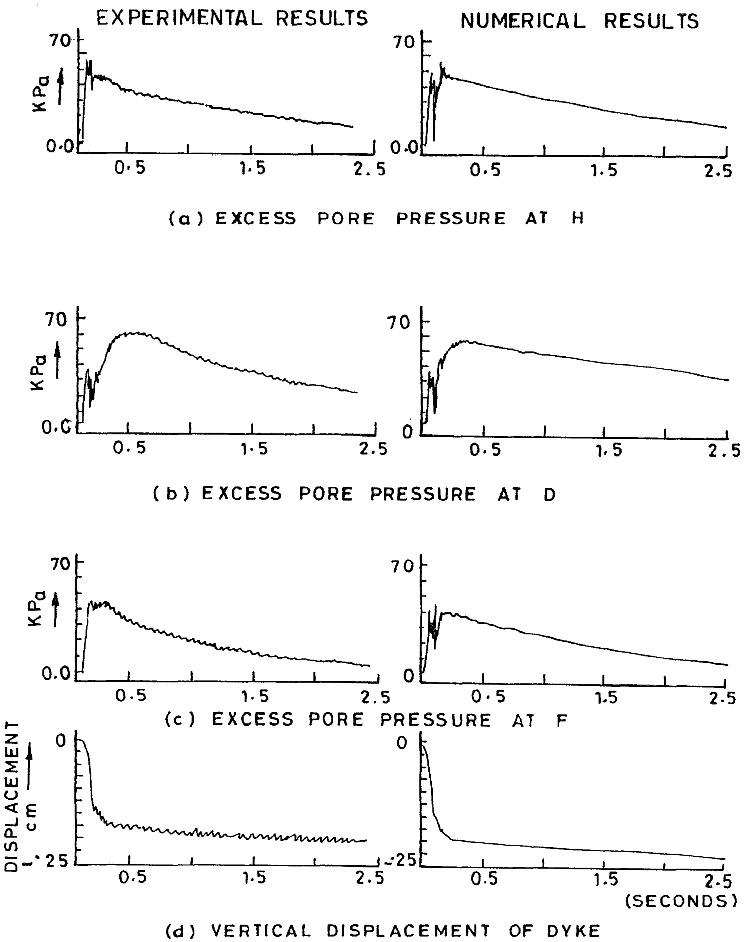

FIG. 2_COMPARISION OF EXPERIMENTAL AND ANALYTICAL RESULTS