Effects of Soil Liquefaction of Seismic Response of Nuclear Power Plants

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Abstract

An analysis procedure, based on the finite element technique, is presented for analyzing dynamic response of structure-foundation systems in excessively large (residual) pore pressure environment. A deterministic model is used to evaluate the seismically induced excess pore pressure distribution and its (pore pressure) effect on foundation response is incorporated in a realistic manner. The proposed technique is used to examine the dynamic response of a model nuclear power plant under cyclic loading. Numerical results are presented to demonstrate the behavior of the system.

1. Introduction

Excessive settlement of foundations due to liquefaction of soil during earthquakes has been found to be the major cause of catastrophic failure and widespread damage of numerous structures [1,4-7].

In order to mitigate such earthquake hazards in the future, it is necessary to develop rational design and analysis technique(s) for structural foundations to withstand the effects of soil liquefaction. Liquefaction resistant design is particularly important for such structures as nuclear power plants where safety is a major concern. This is because the failure of a nuclear power plant during an earthquake will not only cause disruption of services but may also release radio active materials into the environment.

The main objective of this paper is to present a finite element procedure to analyze seismic response of structure-foundation systems, located at a site having potential for soil liquefaction. The proposed procedure explicitly accounts for the dynamic soil-structure interaction effects as well as incorporates the spatial and temporal changes (increase) of pore pressure due to seismic ground shaking. A model nuclear reactor (Fig. 1) partially embedded in saturated sandy soil and subjected to cyclic (horizontal) excition is analyzed and numerical results are presented.

2. Analysis Procedure

2.1 Idealization of a Model Nuclear Power Plant

Figure 1 depicts the plane strain finite element idealization of a model nuclear power plant structure. The site soil consists of layered sand deposits, water table being located at a depth of 5 feet from the ground surface. The material properties used in the analysis are given in Ref. [3].

To examine the influence of excess pore water pressure and resulting soil liquefaction, if any, on the system under consideration, responses for two different cases are evaluated and compared. In the first case, pore pressure buildup in sand is ignored, while in the second case, analysis is performed including the effects of excess pore pressure development and soil liquefaction. A site having strong liquefaction potential under the applied seismic shaking is chosen purposely to demonstrate the consequences of liquefaction on the structure.

2.2 Overview of Finite Element Formulation

The dynamic response of the structure-foundation-soil system in Fig. 1 can be obtained by solving the global equation of motion given by [2,9]:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{R^{(t)}\} \tag{1}$$

in which [M], [C] and [K] = global mass, damping and stiffness matrices, respectively; $\{R^{(t)}\}$ and $\{u\}$ = global load and displacement vectors, respectively; and the overdot denotes derivative with respect to time. Here the Rayleigh damping concept [2] is utilized to evaluate the element damping matrices. Different damping ratios are used for different soil layers.

A computer program is developed to solve eq. (1) using a step-by-step time integration scheme. In the present version of the computer coding, two different implicit time integration schemes, namely Newmark method and Wilson-θ method [2], are implemented.

2.3 Load Vector Due to Excess Pore Water Pressure

It is well known that the vertically propagating shear waves caused by seismic loading will induce excess pore pressure in saturated sand deposits. In the present analysis, such excess pore pressure buildup is evaluated using a deterministic 'pore pressure model' developed by Sherif et al., [8]. Any increase in excess pore pressure, as predicted by the model, is converted into equivalent nodal load (eq. 4) which is then used to augment the load vectors due to inertia, damping etc.

Let Δp be the residual pore pressure developed at time t at a point in an element. This Δp can be treated analogous to body forces and converted to equivalent nodal forces, $\{r_{\Delta p}^{(t)}\}^e$, for a typical element, e, using the relation [10]:

$$\{r_{\Delta p}^{(t)}\}^e = \int_V [B]^T \{n\} \Delta p \, dV \tag{2}$$

where [B] = strain-displacement transformation matrix, and $\{n\}^T = (1\ 1\ 0)$ indicates that Δp is hydrostatic in nature. For the four-noded quadrilateral isoparametric element employed herein [B] can be expressed in an explicit form as:

$$[B] = \begin{bmatrix} \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} \end{bmatrix} \begin{bmatrix} N_1 & 0 & N_2 & 0 & N_3 & 0 & N_4 & 0 \\ 0 & N_1 & 0 & N_2 & 0 & N_3 & 0 & N_4 \end{bmatrix} \tag{3}$$

in which N_i (i = 1,2,3,4) are the shape functions, and x,y represent cartesian coordinates.

The global load vector, $\{R_{\Delta p}^{(t)}\}$, due to excess pore pressure at any given instant of time can be computed from

$$\{R_{\Delta p}^{(t)}\} = \sum_{e=1}^{NE} \{r_{\Delta p}^{(t)}\}^e \tag{4}$$

where NE = total number of submerged soil elements.

2.4 Evaluation of Excess Pore Pressure

In order to implement eq. (4) in the finite element analysis, it is necessary to determine the temporal and spatial variation (buildup) of excess pore pressure (Δp) due to seismic loading. In this study, it is assumed that the pore pressure rise $(\Delta p)_j$, at any given instant of time, due to a randomly varying shear stress history, can be expressed as [8].

$$(\Delta p)_j = (1 - p_{N-1}) \cdot \frac{C_1 \, (N_{eq})_j}{(N_{eq})_j^{C_2} - C_3} \cdot \left\{ \frac{(\tau_N)_j}{\sigma'_{N-1}} \right\}^{\alpha} \tag{5}$$

where (N_{eq}) represents the equivalent number of shear stress cycle, τ_N = shear stress amplitude at Nth cycle, and the subscript j denotes positive (for j=p) and negative (for j=n) shear stress regions, respectively. C_1, C_2, C_3 and α are the associated material parameters for the model. The total Δp at any given cycle is obtained by $\Delta p = (\Delta p)_p + (\Delta p)_n$. To determine the residual pore pressure, p_N, at Nth cycle, Δp is added to the pore pressure at (N-1)th cycle, that is, $p_N = p_{N-1} + \Delta p$. This procedure is employed for all submerged soil elements at each time step; element centroid is used as the reference point in pore pressure computations.

For simplicity, dissipation of pore pressure during seismic shaking is neglected in this study. For short duration earthquake loading, this is expected to have insignificant effects on the end results. Moreover, the on-set of liquefaction at a point in the soil medium is assumed to occur when the residual pore pressure becomes equal to the effective confining pressure at that point. Upon initiation of liquefaction, the shearing modulus G of an element is reduced to zero and the Poisson's ratio is assigned a value close to 0.5. The stiffness and damping matrices of liquefied elements are reevaluated, based on the modified properties. Further details of the proposed analysis procedure are given elsewhere [3].

3. Numerical Results

The (finite element) analysis procedure outlined in the preceding section is used to evaluate the dynamic response of a model nuclear power plant subjected to cyclic loading (frequency = 0.5 Hz and amplitude = 0.125g, g being the acceleration due to gravity) at the rigid bedrock, Fig. 1.

The horizontal and vertical displacement histories of five representative points, P_1, P_2, P_3, P_4 and P_5 (see Fig. 1), are shown in Figs. 2 and 3, respectively. Some general remarks can be made regarding these results.

At the initial stage (up to about 2 sec.) of loading process, the response is basically unaffected due to pore pressure rise. After this period, the effects of residual pore pressure become predominant. Also, the effects of soil-structure interaction (SSTIN) are seen to be more significant at larger values of t. Although the points P_1 and P_2 are both located on the surface, P_2 being closer to structure than P_1, they respond differently, under the same excitation, indicating the severity of SSTIN. The horizontal displacements at points P_3 and P_4, located at the bottom corners of the foundation (Fig. 1), are basically of same magnitudes and in-phase, while their vertical displacements are out-of-phase by about 180°. This indicates that the structure undergoes large rocking motion, which increases disproportionately as the pore pressure buildup continues.

The distributions of (normalized) residual pore pressure, at two selected times, namely 2 and 8 seconds, are presented in Fig. 4. As the distribution of pore pressure contours is symmetric about the (vertical) centroidal axis of the structure, results for half of the domain are shown. Because of the very high confining pressure under the structure, pore pressure rise in this region remains relatively small. Also, the liquefaction is seen to have initiated at shallow depths and propagated to regions away from the structure, and at larger depths. A pictorial representation of the expansion of liquefied zones is presented in Fig. 5. In this figure a particular pattern indicates the time range during which the elements in that group were liquefied. It is observed that the elements near the foundation corners and located at shallow depths liquefy first, due to the large shear stresses induced by rocking motions of the structure and resulting rapid increase in residual pore pressure. The expansion of the liquefied zones appears to be in good agreement with similar experimental results reported in Ref. [6].

4. Concluding Remarks

In this paper, a numerical procedure, based on the finite element method, is presented for analyzing dynamic response of structure-foundation systems in excessively large (residual) pore pressure environment. The effects of soil-structure interaction and soil liquefaction, if any, due to seismically induced shear stresses, on the behavior of a model nuclear power plant structure are examined. Despite several simplified assumptions made, the analysis technique, in general, appears to provide encouraging numerical results for residual pore pressure buildup and distribution, on-set and propagation pattern of soil liquefaction and resulting foundation response.

5. References

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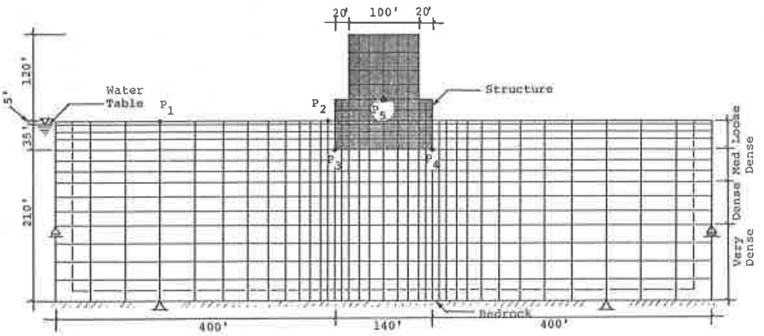

Figure 1 Finite Element Idealization of a Model Nuclear Power Plant and Underlying Soil Deposit.

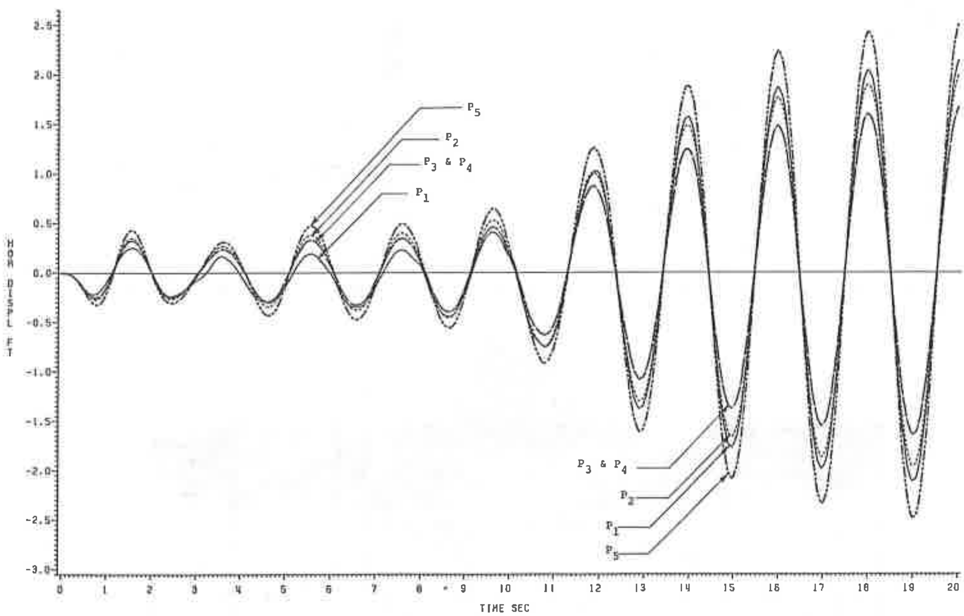

Figure 2 Horizontal Displacement Histories at Points P_1, P_2, P_3, P_4, and P_5.

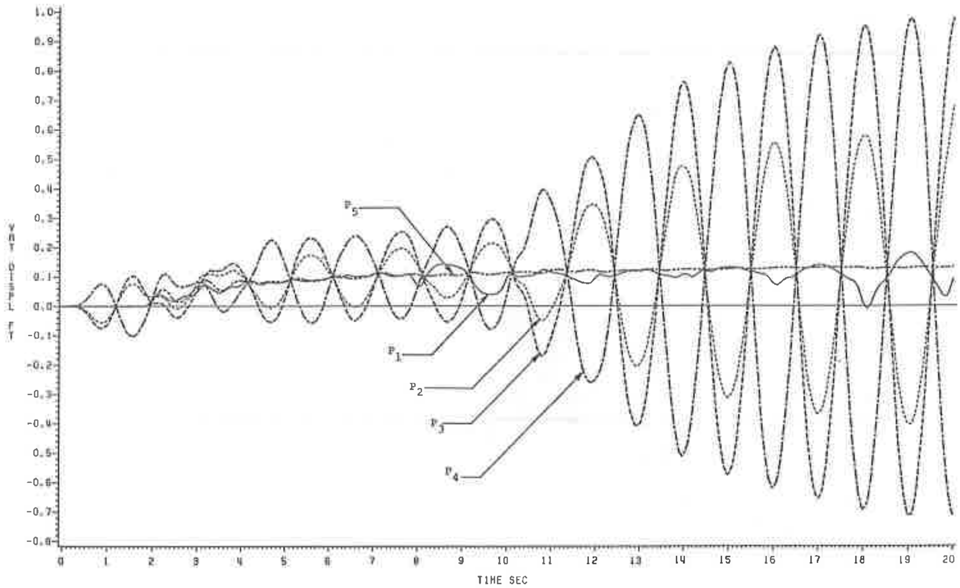

Figure 3 Vertical Displacement Histories at Points P_1, P_2, P_3, P_4, and P_5.

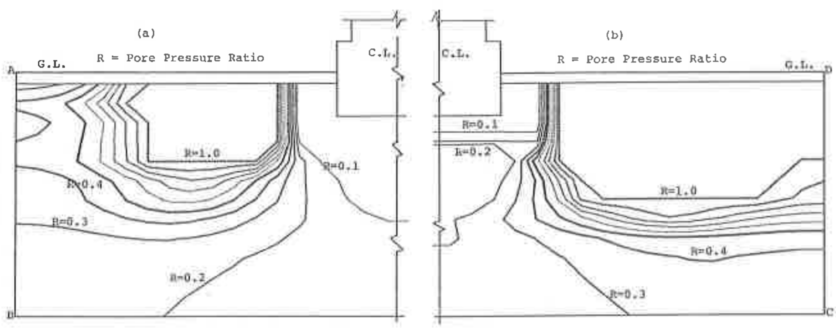

Figure 4 Pore Pressure Contours at Time (a) 2 Seconds and (b) 8 Seconds.

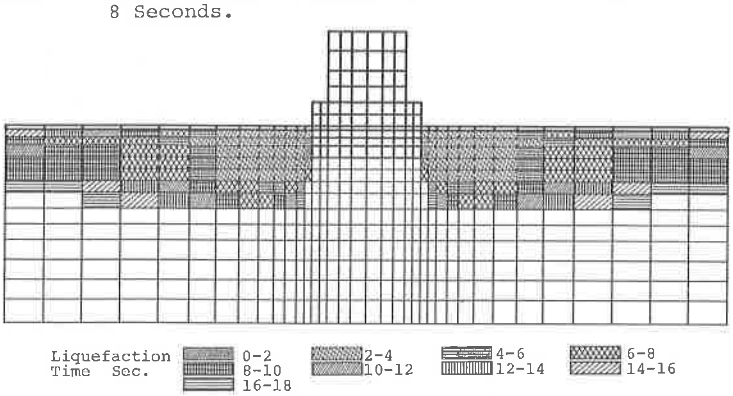

Figure 5 Temporal Expansion of Liquefied Zones.