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Paper No. 1048. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

DYNAMIC RESPONSE OF FLUID-SATURATED POROUS SOILS USING SHOCK TUBE TESTS

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ABSTRACT

An experimental and numerical program to investigate the phenomenon of one-dimensional wave propagation in fluid-saturated porous soils was conducted. Laboratory samples of uniformly graded saturated Ottawa sand were placed in a rigid walled shock tube and subjected to short duration pressure pulses. The measured pore pressure time histories were compared with predictions that had been obtained using an elastic two phase finite element model. For the conditions simulated in the laboratory experiments, excellent agreement between the measured and predicted pore pressure response was achieved.

KEYWORDS

One Dimensional Wave Propagation; Numerical Model; Laboratory Experiments

INTRODUCTION

Fluid saturated sands have been implicated in numerous failures of structures during dynamic loads. As a result of these dynamic events, localized areas of saturated soils may develop very high pore pressures resulting ultimately in liquefaction. Researchers have studied the liquefaction phenomenon with the goal of predicting the development of dynamic load induced pore pressures and the consequent dynamic response of engineered structures founded on the affected soils.

LITERATURE REVIEW

Theoretical Models

The theoretical prediction of dynamic response of saturated soils is of importance in analyzing many engineering problems including those related to ground motion, such as liquefaction and soil-structure interaction. As a result, analytical and numerical models for wave propagation through saturated soils have become the focus of study by numerous researchers. In an attempt to describe the effects of liquefaction, two distinct approaches have been widely used over the years.

Seed and Lee (1966) used the principles of structural dynamics to develop a methodology to account for pore pressure build up during dynamic loading events. The stress history was evaluated by a finite element analysis of the system under an applied acceleration history. Laboratory cyclic stress tests of the material were carried out until a stress history equivalent to that from the numerical model was obtained. This approach, which Sandhu (1985) called the engineering approach, has been studied and advanced by many researchers in the years following the original work of Seed and Lee (1966). This technique has been used by Seed and his co-workers to analyze a number of case histories (e.g., Idriss and Seed (1970); Seed and Lee (1972)). However, as Sandhu (1985) observed, the method is deficient in several respects. Sandhu noted that the approach had only been used for one-dimensional cases, and it could not be extended to two and three-dimensional cases. The engineering approach requires considerable experience and judgment to get useful results, and its extension into the area of post-liquefaction deformation prediction has been difficult.

A continuum mechanics approach as proposed by Biot (1956) is a general theory for wave propagation in fluid-saturated linear elastic isotropic porous solids. The dynamic equilibrium equations were derived from a Lagrange equation which was set up assuming the existence of viscous dissipation and strain energy functions. As a result of Biot's theory, several analytical as well as numerical solution techniques have been developed for solving Biot's equations.

Among the analytical procedures based on Biot's formulation, Garg *et al.* (1974) considered the response of a fluid-saturated linear elastic isotropic medium subjected to both harmonic and transient pulses. Garg *et al.* (1974) used Laplace transform techniques to derive closed-form analytical solutions for the limiting cases of weak and strong viscous coupling. However, an analytical solution for the general case of transient loading could not be obtained. Simon *et al.* (1984) presented a one-dimensional analytical solution under varying types of traction boundary conditions where the solid and fluid materials satisfy Biot's dynamic compatibility relation. Hong *et al.* (1988) extended Garg's formulation for the "weak" and "strong" viscous coupling to develop analytical solutions for four different types of velocity boundary conditions. These included, unit step, sine, ramp, and spike functions. They concluded that the existence of two compression wave modes (solid and fluid) which propagate at different velocities is apparent. Analytical solutions to wave propagation in fluid-saturated porous media are very limited and can not be obtained for complex loading and boundary conditions. The existence of analytical solutions to simplified problems of wave propagation in saturated soils are essential to verify the accuracy of numerical models.

Numerical procedures for approximate solutions to Biot's equations for the dynamic response of fluid-saturated porous media have been developed by several researchers. Ghaboussi and Wilson (1972) used variational principles to develop a two field finite element formulation for the problem. The field variables used were the solid displacement and the displacement of the fluid relative to the solid. At that time, with no exact (analytical) solutions developed, the procedure could not be verified. Using the work of Garg *et al.* (1974) as a benchmark, Sandhu *et al.* (1984, 1986, 1988) developed several finite element procedures for two and three-field formulations and compared the solutions for the two limiting cases of viscous coupling with Garg *et al.* (1974). The three-field formulation used solid displacement, relative displacement of the fluid with respect to the solid, and the intrinsic pore fluid pressure as the nodal degrees of freedom. Sandhu *et al.* (1986) also introduced the effects of reflections of waves at the boundaries. Simon *et al.* (1986) evaluated the effects of higher order, mixed and hermitean finite element procedures using one-dimensional models. Accuracy was established by comparing finite element results with a one-dimensional analytical solution presented by Simon *et al.* (1984). Sandhu *et al.* (1987a, 1987b) presented a finite element formulation based on Galerkin's approximation of Biot's equations of motion for wave propagation in linear elastic saturated soils. Wilson's step forward integration scheme was used for time domain integration. A finite element computer program DALES (Dynamic Analysis of Linear Elastic Soils) was developed. It included one-dimensional (linear, quadratic, and cubic Hermite) elements as well as two-dimensional (bilinear and bi-quadratic) elements. The results of the finite element solution procedure were compared with known analytical solutions for one-dimensional wave propagation. A good agreement for pore pressure time histories was observed for the one-dimensional Hermite element. Dreger (1995) extended DALES to include arbitrary time varying loading.

Experimental Investigations

One-dimensional wave propagation in soils has been studied experimentally for over two decades. Hampton (1965) conducted experiments using a horizontally-mounted shock tube to study the effects of pore air pressure in a soil subjected to shock waves. Akai *et al.* (1974) conducted studies on wave propagation in saturated cohesive soils by means of a triaxial shock tube. The shock tube was connected to a triaxial chamber which contained a cylindrical clay specimen. The initial loading consisted of a pressure pulse with a steep front that gradually decayed. The use of a vertical shock tube was developed by van der Kogel *et al.* (1981) for analyzing the effects of compressional wave propagation in a fixed column of porous media. Their success was largely due to the shock tube's ability to generate reproducible step loading conditions on the porous system. Van der Grinten *et al.* (1985) complemented van der Kogel *et al.'s* (1981) work by making comparisons between theoretical predictions and experimental results for the two cases of dry air filled pores and completely water saturated pores. Comparisons were made for wave amplitude, wave velocities, and damping characteristics and good agreement between the theoretical and experimental results was obtained. However, the pore pressure, the excess of which can lead to liquefaction, was not measured. Kuo (1990) proposed a robust experimental program to measure pore pressure time histories for one-dimensional wave propagation through saturated media using a vertically-mounted shock tube. This work was limited to conducting reliable experimental tests with repeatable results. Limited comparison of the experimental observations with theoretical predictions was presented.

The study of pore pressure response in saturated sands is important due to its liquefaction potential under seismic and blast loading. Several experimental and theoretical studies have been carried out to study the wave propagation phenomenon in fluid saturated porous soils, but a comparison of experimental observations with numerical predictions for pore pressure time histories is lacking in the literature. This study aims to fill this void. The experimental pore pressure measurements are compared with those obtained from the numerical model DALES.

EXPERIMENTAL PROGRAM

Properties of Ottawa Sand & Dow Corning Fluid

Ottawa sand which is a fine to medium grained silica sand was used as the test solid. Results of laboratory tests conducted by Wolfe *et al.* (1986), to determine the material properties of the Ottawa sand, were used in this experimental program. The following properties were used for Ottawa sand:

Specific Gravity = 2.65
Bulk Modulus (Grains) = 370000 kg/cm^2
Poisson's Ratio = 0.16
Porosity = 0.61
Total Mass Density = 1.62 g/cm^3
Bulk Modulus (Skeleton)= 240 kg/cm^2
Modulus of Elasticity = 483 kg/cm^2
Absolute Permeability = 3.10 x10^{-7} cm^2

Dow Corning silicone oil was used as the sample fluid. The density of the silicone fluid ($\rho = 0.82$ g/cm^3) is close to water but it is available in a wide range of viscosities. Additionally complete saturation of the sample could be readily achieved. The bulk modulus of the fluid was determined by measuring the velocity of the shock wave in a test with fluid only. The properties of the silicone fluid used in the test are summarized below:

Kinematic Viscosity = 1.0 cStoke
Intrinsic Bulk Modulus= 7,550 kg/cm^2

Test Facilities

The components used in conducting the shock tube experiments consisted of a vertically-mounted shock tube, pressure transducers mounted in the side of the tube, an amplifier, and a data acquisition system to collect and display the data. A schematic diagram of the experimental setup is shown in Fig. 1.

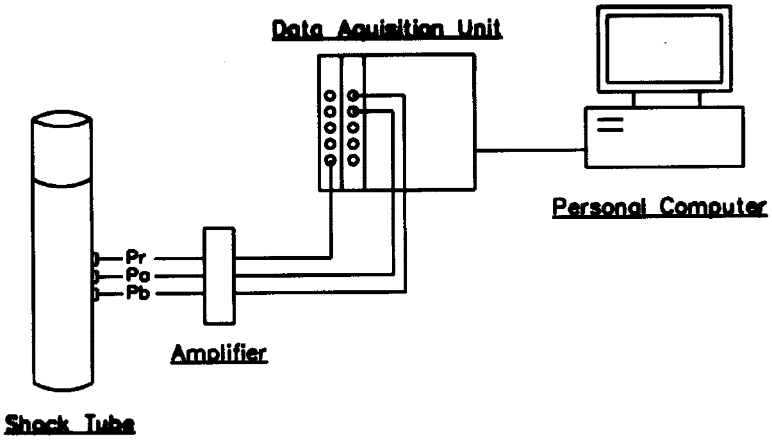

Fig. 1. Shock Tube Experimental Setup

The shock tube used for the experimental program was a closed-ended steel tube measuring 92 cm in length and 8 cm in diameter with a wall thickness of 0.5 cm. A typical detail of the sample in the shock tube is shown in Fig. 2. As shown in Fig. 2, the tube consisted of a high pressure and a low pressure section separated by a mylar membrane. Mylar was selected because on bursting, it quickly released the high pressure and produced a ramp type loading condition with a small rise time. The test chamber of the tube consisted of two sections, a saturated sand sample section and a fluid only section. The saturated sand sample measured 29.2 cm in length. The 37.5 cm of silicone fluid column on top of the sample was used as a wave guide for the pressure pulse. Three pressure transducers Pr, Pa and Pb were mounted in the wall of the steel shock tube. The transducers were placed at distances of 29.8, 26.0 and 22.2 cm from the bottom of the sample. The reference transducer (Pr) was placed in the fluid column, just above the saturated sand - fluid interface. The reference transducer monitored the load applied to the top of the saturated sand sample.

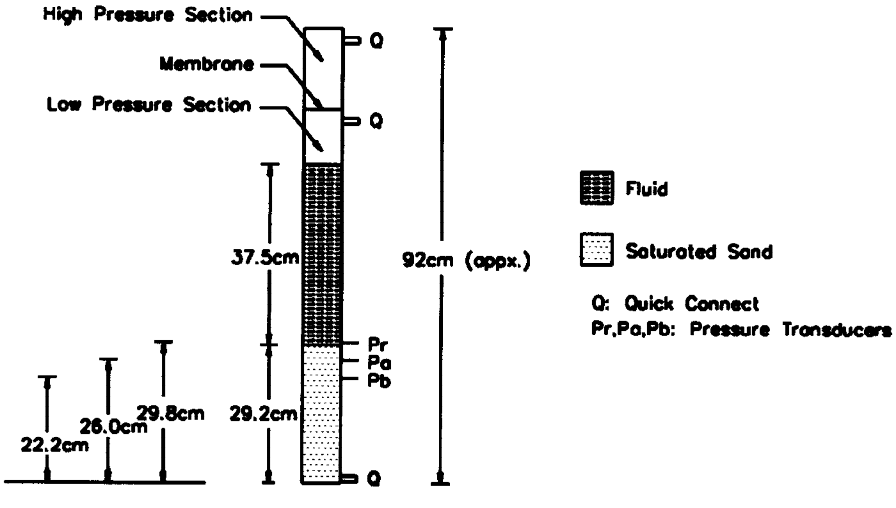

Fig. 2. Sketch of Sample In Shock Tube

Entran EPI-050 pressure transducers were used to record the dynamic pore pressure time histories. This device was selected for the experimental program because it has a diameter of 1.27 mm and a natural frequency of 1-3 MHz.

In order to record the response of the propagating stress waves in the sample, a Nicolet Multipro Data Acquisition System, with the capability of sampling at a rate of 1 million samples per second per channel, was employed for the task of collecting data. The actual data collection rate was 200,000 samples per second on each channel.

Test Procedure

The saturated sand sample was placed at the bottom of the shock tube up to a height of 29.2 cm. Silicone fluid was poured on top of the sample to a height of 37.5 cm. A thin mylar sheet was then placed between the high pressure reservoir and test section. Both the high pressure and test sections were initially pressurized to approximately 1 kg/cm^2. Air pressure was then applied to the high pressure section until the membrane broke. This usually occurred between 4 - 5 kg/cm^2. Breaking the membrane led to the release of pressure from the high pressure section, which loaded the fluid column and saturated sample. Propagation of the resulting stress waves through the sample were recorded at three different locations along the length of the shock tube. A typical pressure time history is shown in Fig. 3.

NUMERICAL MODEL “DALES”

DALES (Dynamic Analysis of Linear Elastic Soils) is a finite element numerical model developed by Sandhu *et al.* (1987a, 1987b) for dynamic analyses of two phase materials. The finite element formulation is based on Galerkin’s approximation of Biot’s equations of motion for the dynamics of linear elastic saturated porous media and uses Wilson’s step-forward time domain integration scheme for the numerical analysis.

The model is capable of using linear, quadratic, and cubic Hermite polynomial interpolation over one-dimensional elements. For two-dimensional problems, bilinear and biquadratic isoparametric elements are used. The linear and quadratic elements use the solid displacement and relative fluid displacement as the nodal degrees of freedom. For these elements, the pore pressures are evaluated at the centers of the elements from the gradients of displacements. Hence, the calculated pore pressures are not continuous when linear and quadratic elements are used. The Hermite element overcame this difficulty by adding the gradients of solid and relative fluid displacements as additional degrees of freedom. Thus, the pore pressures can be evaluated directly at the nodal points, making the Hermite element a very useful tool in this study. Originally the input for the dynamic load for DALES could be given as a Sine, Box, Ramp, or Spike type excitation. In order to use DALES to model the experiments performed in this study, the numerical model was modified to allow for arbitrary loading conditions. This allowed the use of the measured pressure response of reference transducer (Pr) as the dynamic excitation for the numerical model. The Hermite element (0.635 cm in length) and a time step of 5μs were used for the present study.

COMPARISON OF RESULTS

An initial confining stress of approximately 1 kg/cm^2 was applied to the test section of the shock tube before breaking the membrane. The actual response measured by the pressure transducers is a sum of the static confining pressure and the change in pressure due to the applied dynamic shock load. All the results presented here show the dynamic change in pore pressure experienced by the sample compared with numerical predictions.

The observed experimental pressure time history at the reference transducer (Pr) is shown in Fig. 3. It shows a small rise time of approximately 0.4 ms and a peak pressure value of 7.3 kg/cm^2. The shock wave traveling through the sample reflects and refracts several times at the bottom of the tube, at the interface between saturated sand and fluid, and at the top of the fluid. This gives rise to the oscillatory pressure response shown in Fig. 3. The magnitude of the peak pore pressure reduces with each oscillation due to friction between solid and fluid phases.

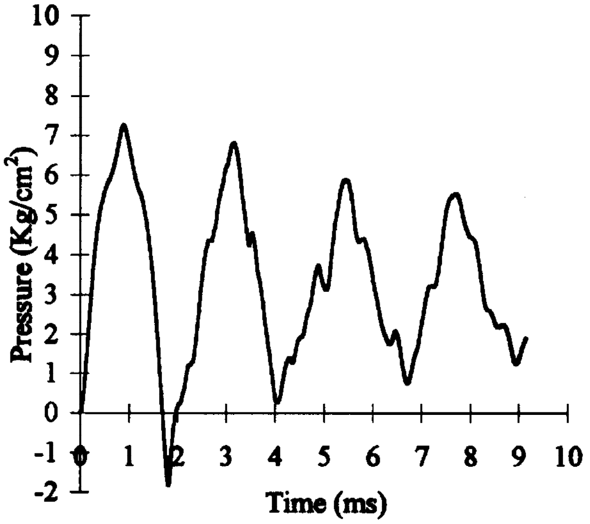

Fig. 3. Measured Pressure Response of Transducer Pr

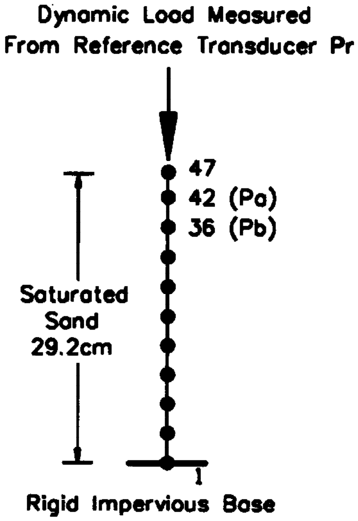

Fig. 4. Finite Element Mesh

The finite element model DALES was used to numerically model the shock tube experiments. The Hermite element was used for spatial discretization. The finite element mesh used for the study is shown in Fig. 4. The experimentally measured pore pressure response from the reference transducer (Pr) was the applied dynamic loading on the saturated sand sample at node 47.

Figures 5 and 6 present a comparison of the pore pressure time histories for the experimental observations and the numerical model, for transducers Pa and Pb, respectively. For transducer Pa, the numerical predictions of pore pressure time histories exhibit excellent agreement with experimental observations. This is especially true up to about 1 ms. The numerical results are in phase with the experimental predictions for the duration of the time history plotted. Transducer Pb exhibits good comparison between the numerical and experimental results. However there is a slight lag in the calculated results. The calculated peak values of pore pressure for transducers Pa and Pb, are within 14% and 18%, respectively, of the observed values. Yet, the comparison is still excellent over the full 9 ms for which experimental data was collected.

Figure 7 shows a plot of the pore pressure distribution along the length of the shock tube specimen as predicted by the numerical model before the wave hits the bottom of the shock tube. The wave speed in the saturated sample is obtained from Fig. 7 as 114 x 10^3 cm/s. The circular data points are the experimental pore pressure measurements and they are in good agreement with the numerical model predictions. Figure 8 shows the pore pressure distribution predicted by the numerical model after the wave has completed approximately seven cycles. A cycle consists of the wave traveling from the top of the fluid column to the bottom of the sample and reflecting back from the bottom to reach the top of the fluid column. It is evident that even after seven cycles, the pore pressure time distribution predicted by the numerical model agrees well with the experimental observations.

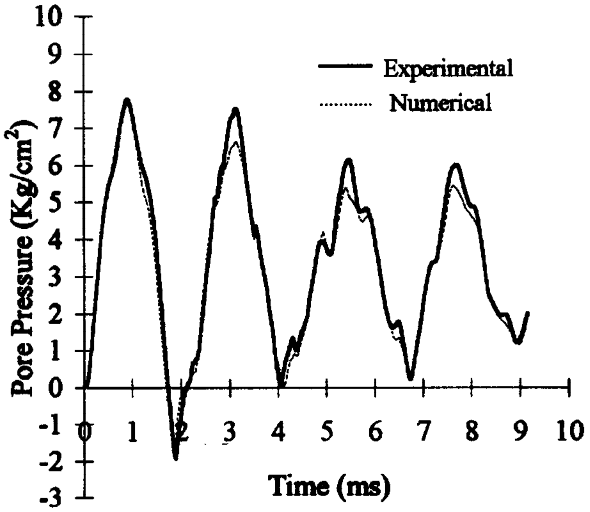

Fig. 5. Pore Pressure Response of Transducer Pa

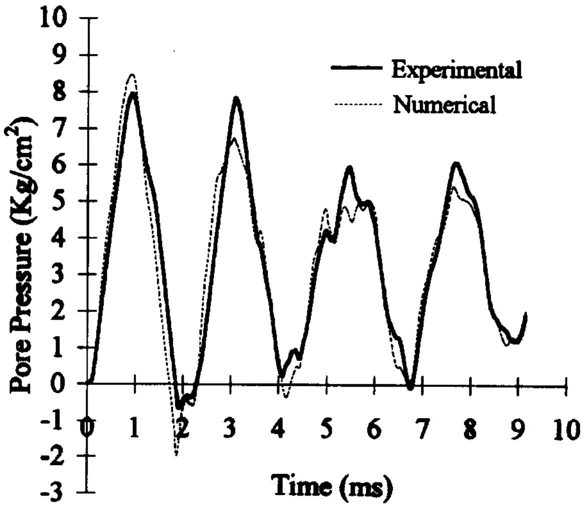

Fig. 6. Pore Pressure Response of Transducer Pb

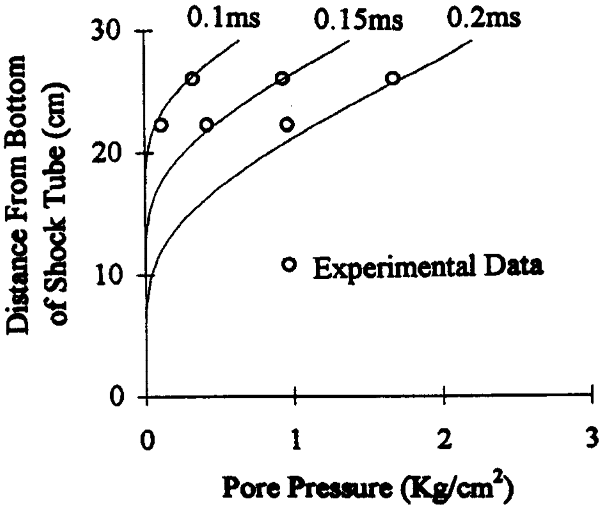

Fig. 7. Pore Pressure Distribution Along Length Of Shock Tube For Time = 0.1,0.15 & 0.2 ms

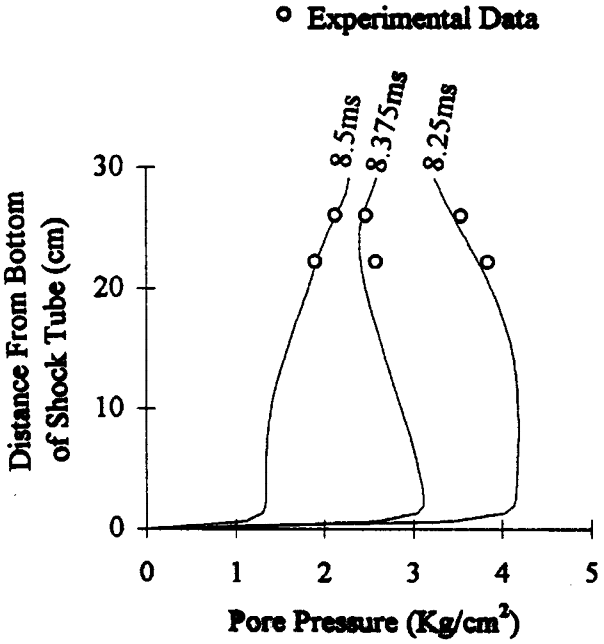

Fig. 8. Pore Pressure Distribution Along Length Of Shock Tube For Time = 8.25,8.375 & 8.5 ms

CONCLUSIONS

The results of a combined laboratory and theoretical program to study the dynamic behavior of saturated sand are presented. The vertically-mounted shock tube with a saturated soil sample topped by a fluid column is shown to be a reliable means of generating stress waves in saturated soils. The pore pressure time histories observed from the laboratory experiments are in excellent agreement with the numerical results predicted by the two phase finite element program DALES. Verification of the numerical model for different combinations of fluid and solid is in progress.

REFERENCES

Akai, K., M. Hori, and T. Shimogami (1974). Study on Stress Wave Propagation Through Saturated

Cohesive Soils by Means of Triaxial Shock Tube. *Proceedings of the Japanese Society of Civil Engineers*, 228, 99-108.

Biot M.A.(1956). Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid - Parts I and II. *Jour. Acous. Soc. Amer.*, 28-2, 168-191.

Dreger, B.A..(1995). *Verification of Predictions of Dynamic Response in Fluid-Saturated Porous Media Using Shock Tube Tests,* MS Thesis, The Ohio State University, Columbus, Ohio.

Garg, S.K., A.M. Nayfeh, and A.J. Good (1974). Compressional Waves in Fluid Saturated Elastic Porous Media. *Jour. App. Phy.,* 45, 1968-1974.

Ghaboussi, J., and E.L. Wilson (1972). Variational Formulation of Dynamics of Fluid-Saturated Porous Elastic Solid. *Journal of Engineering Mechanics Division, A.S.C.E.,* 98, 947-963.

Hampton, D. (1965). Pore Air Pressure in Soil Subjected to Shock Wave. *Journal of the Soil Mechanics And Foundation Division, A.S.C.E.,* 91, 41-56.

Hong, S.J., R.S. Sandhu, and W.E. Wolfe (1988). On Garg's Solution of Biot's Equations for Wave Propagation in a One - Dimensional Fluid-Saturated Elastic Porous Solid. *Int. Jour. of Num. Anal. Methods in Geomech.*, 12, 627-637.

Idriss, I.M., and H.B. Seed (1970). Seismic Response of Soil Deposits. *Proceedings Amer. Soc. Civ. Engrs., Jour. Soil Mech. Found. Div.,* 96, 631-638.

Kuo, C.Y. (1990). *Dynamic Pore Pressure Response of Saturated Ottawa Sand - Shock Tube Tests,* MS Thesis, The Ohio State University, Columbus, Ohio.

Sandhu, R.S., B.L. Aboustit, S.J. Hong, and M.S. Hiremath (1984). *A Computer Program for Consolidation and Dynamic Response Analysis of Fluid-Saturated Media,* Geotechnical Engineering Report No. 14, OSURF 715107-84-5, AFOSR Grant 83-0055.

Sandhu, R.S. (1985). *Mechanical Behavior of Saturated Soils - A Review,* Geotechnical Engineering Report No. 10, OSURF 715927-85-1, AFOSR Grant 83-0055.

Sandhu, R.S., W.E. Wolfe, and H.L. Shaw (1986*). Analysis of Dynamic Response of Saturated Soils Using a Three-Field Formulation,* Geotechnical Engineering Report No. 20, OSURF 716894-86-3, AFOSR Grant 83-0055.

Sandhu, R.S., W.E. Wolfe, and M.S. Hiremath (1987a*). Finite Element Analysis of Wave Propagation in Saturated Soils,* Geotechnical Engineering Report No. 22, OSURF 717885-87-6, AFOSR Grant 83-0055.

Sandhu, R.S., W.E. Wolfe, and M.S. Hiremath (1987b). *Computer Program DALES (Dynamic Analysis of Linear Elastic Soils),* Geotechnical Engineering Report No. 27, OSURF 717885-87-7, AFOSR Grant 83-0055.

Sandhu, R.S., W.E. Wolfe, and H.S. Chohan (1988). *Motion and Stability of Saturated Soil Systems Under Dynamic Loading,* Geotechnical Engineering Report No. 31, OSURF 717885-88-4, AFOSR Grant 83-0055.

Seed, H.B., and K.L. Lee (1966). Liquefaction of Saturated Sand During Cyclic Loading. *Journal of Soil Mechanics and Foundation Division, A.S.C.E.*, 93, 105-134.

Seed, H.B., and K.L. Lee (1972). Test Procedures for Measuring Soil Liquefaction Characteristics. *Journal of Soil Mechanics and Foundation Division, A.S.C.E.*, 97, 1099-1118.

Simon, B.R., O.C. Zienkiewicz, and D.K. Paul (1984). An Analytical Solution for the Transient Response of Saturated Porous Elastic Solids. *Int. J. Numer. Anal. Methods Geomech.*, 8, 381-398.

Simon, B.R., J.S. Wu, and O.C. Zienkiewicz (1986). Evaluation of Higher Order, Mixed and Hermitean Finite Element Procedures for Dynamic Analysis of Saturated Porous Media Using One - Dimensional Models. *Int. J. Numer. Anal. Methods Geomech.*, 10, 483-499.

van der Grinten, G.M. Jos, Marinus E.H. van Dongen, and H. van der Kogel (1985). A Shock-tube Technique for Studying Pore-Pressure Propagation in a Dry and Water-Saturated Porous Medium. *Jour. App. Phy.*, 58, 2937-2942.

van der Kogel, H., C.H. van Loon Engels, and P.A. Ruygrok (1981). Wave Propagation in Porous Media, Shock Tube Experiments. *Proceeding of the 10th International Congress on Soil Mechanics and Foundation Engineering, Soil Dynamic Section, Stockholm*, 253-356.

Wolfe, W.E., R.S. Sandhu, and V.E. Amato (1986*). Preliminary Test on Liquefaction of Ottawa Sand,* Geotechnical Engineering Report No. 19, OSURF 716814-86-2, AFOSR Grant 83-0055.