# Wave Propagation in Porous Media, Shock Tube Experiments

## Propagation des Ondes dans un Milieu Poreux, Expériences dans un Tube à Choc

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SYNOPSIS

Wave propagation in saturated porous media attracts the interest of research workers in many disciplines, e.g.: geophysicists, civil engineers and civil defense workers. Especially the aspect of pore pressure became more evident for earthquake and blast problems.
In order to get more insight into the propagation of pore pressure during transient loading a limited shock tube study has been performed. Pore pressure and total pressure recordings due to shock loading of a "sand pile" have been obtained. This type of loading is especially suited for verifying theoretical models. Three cases are considered; the dry, the unsaturated and the "almost" saturated case. Although the measurement of "pore" pressures within an unsaturated porous sample during transient loading is still at its infancy, the structure of the recordings is interesting. The emerging "two-wave" form and the trends towards the saturated case are in agreement with the established theoretical results.

INTRODUCTION

The interest in the soil mechanics community for wave propagation in saturated soils was mainly generated due to the liquefaction evidence after the 1964 Niiagata and 1964 Alaska earthquakes. Before these events the explosion community e.g. Ivanov (1967) and the oil companies showed interest in the subject, e.g. Geertsma (1961).
From a theoretical point of view one of the earliest attempts to come to a description of the above mentioned phenomena have been made by Biot (1956) and De Josselin de Jong (1956). They used linear theories. Later work by Nikolaevskii (1966) and Garg (1975) was addressed to the non-linear theory. The Biot concept has been used successfully by the oilcompanies for identifying the contents of earth layers. Although many non-linear models and codes are now available or being developed, similar rigorous results on the experimental site seem to be lacking so far.
Ruygrok (1980) performed extensive experiments and showed pore pressure response due to surface impulse of "almost" saturated and dry sands in a large scale experiment. During the dynamic event recordings of total stress measurements and strain measurements within the soil were obtained. Verification runs for this geometry have been made with the SATURN code which employs a multi-phase model developed by Garg et al.(1974) The code has also been applied by Sweet et al (1979) to other geometries such as the dynamic loading of a retaining wall surrounded by saturated soil. In order to test the code and obtain general insight, analytical solutions for special cases were generated by Van der Kogel (1980) for wave propagation in an anisotropic saturated porous medium.

Although most of the attention in the soil mechanics community so far focused on the earthquake related shear effects in saturated soils, recently in the Western World one got interested in the blast related compression effects (1978).
Two "shock tube" experiments especially addressed theirselves to the question of pore pressure propagation due to compression effects. Hampton (1965) studied the propagation of an air impulse ("short" pulse ~ 100 - 150 msec) and True (1969) investigated the propagation of an air and water/air impulse (long pulse ~ 1 sec.). True tried to explain the observed air pressure phenomenon in the framework of a diffusion theory. As far as damping concerned this was not entirely satisfactory. Some unexplained phenomena took place in the "almost" saturated case, which were attributed to the interaction of soil and the tube.
Perry (1972) performed a blast experiment in a large diameter tank. It was concluded that liquefaction is influenced by the boundary conditions (surface covering by membrane). More recently Studer (1977) in Switzerland performed shock tube experiments in saturated sands. The results of 2 pilot test series using a horizontal shock tube were reported. Liquefaction was observed in loose and medium dense sand due to shock loading.
From the results of True's experiments it seemed that additional experiments might add information needed to get a better description of pore pressure propagation due to impact.

EXPERIMENTAL SET UP

The shock tube experiments reported here had a

limited character. The shock tube was selected because it has the ability to generate a simple and reproducable step-loading in a fluid. The main purpose was to identify the effects of a change in pore fluid on the wave propagation in porous media. At this stage a simplified constitutive behavior of the skeleton was considered and therefore the sand grains were glued in order to prevent slipping.
Because in True's experiments there was concern about the shear interaction of the wall and the skeleton, this problem was avoided by introducing a fluid layer of approximately 1 mm between the wall and the sample. Furthermore the sidewalls of the sample were coated with an epoxy spray in order to prevent fluid flow through side walls. Top and bottom of the sample were open. The bottom was supported by a soft foam.
The shock tube is located at the University of Eindhoven, Department of Physics and has been used to study wave propagation through bubbly fluids. It is especially suited for generating shocks in water due to its vertical position and very thick walls.
A sample was prepared by mixing a two-component glue with a sieve fraction of 250-500µm sand. This is a routine procedure for preparing porous stones for triaxial apparatus at the Delft Soil Mechanics Laboratory. The sample had a diameter of 0,075m and a length of 0,90m. The coefficient of permeability for water was ~ 7,1 $10^{-5}$ m/s and the porosity was ~ 0,30. The sample was instrumented with three miniature pore pressure gauges (type Druck PDCR 42) without filters and a total pressure meter (type URS). The locations of the pore pressure gauges, side on position, were at 0,02 m, 0,12 m, 0,22 m from the top of the sample. The total pressure gauge, face on position, was at 0,37 m from the top of the sample. (see fig. 1). The reference pressure

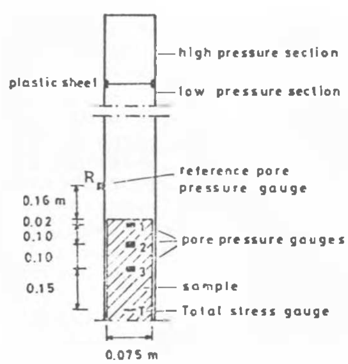


**Fig. 1 Sketch of shock tube.**

behind the pore pressure sensors was ~ 100 kPa. A reference pressure gauge (type Kistler 603B) was located 0,16m above the sample in order to register the input signal. The high pressure section of the shock tube was pressurised at 200 kPa for all the reported experiments. First a series of dry experiments were performed, thereafter water was injected slowly from the bottom until the water level was above the sample and the same experiments were performed. After these series the shock tube was kept under vacuum for a couple of months and by that raising the saturation degree of the porous sample.

RESULTS

For the dry case, in fig. 2, we note that the step loading at the boundary is degenerated in a more slowly rising signal. Furthermore we note that a signal arrives at early times at the total pressure gauge. This is now attributed to the following: When the air shock hits the sample at least two waves emerge. The first one is mainly carried by the stiff skeleton (in terms of pressure) and the second one pressurizes the pore air due to sustained pressure at the boundary. We also note the reflected wave from the sample travelling upwards in the form of the second jump in the reference gauge R.

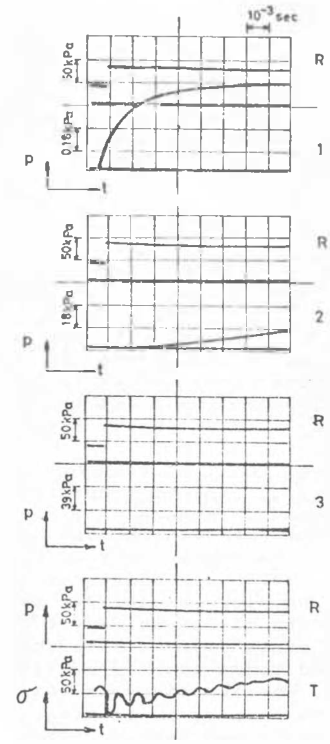


**Fig. 2 Pore pressure (gauges 1, 2 and 3), totale pressure ( gauge T ) and reference gauge ( R ) response for the dry case.**

For the unsaturated case, in fig. 3, we note that there is also a well identifiable two wave structure. However, during the first wave passage the "pore" pressure responds clearly. This is now attributed to the fact that the pore fluid is stiffer with respect to the former case and responds more clearly on skeleton strains. Furthermore we note that the second rise is much quicker than in the dry case.

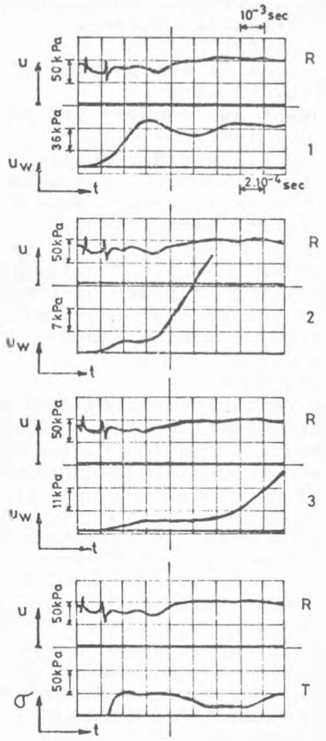


Fig.3 "Pore" pressure (gauges 1, 2 and 3), totale pressure (gauge T) and reference gauge (R) response for the significantly un saturated case.

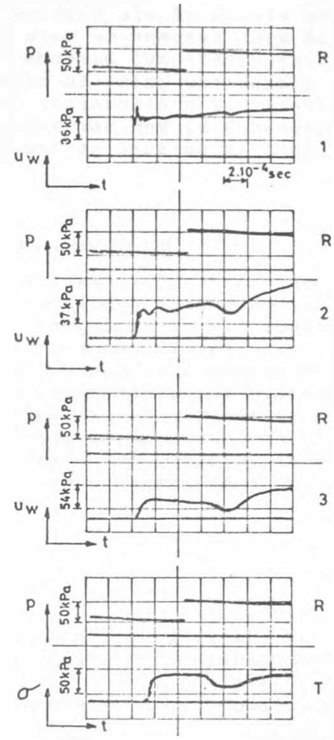


Fig.4 "Pore" pressure (gauges 1, 2 and 3) totale pressure (gauge T) and reference gauge (R) response for the "almost" saturated case.

Finally the "almost" saturated case in fig. 4 shows a quick and large response of the "pore" pressure gauges with a late time effect in "pore" pressure rise. We also note the dips in the signals which are attributed to reflections from the bottom.
It should be remarked at this point that the results presented here should be used with great care for quantitative purposes.
Although we made a considerable effort to evaluate the response of the pore pressure gauges mounted in the site walls of shock tubes in air and water, e.g. Willems (1980), this answers not conclusively the question of the response of gauges within the sample. Especially in the unsaturated case. Ruygrok (1980) has performed some preliminary analysis on this subject and on the effects of inclusion of a total stress gauge.

Calculations by Van Loon-Engels (1979) with the SATURN code (which uses the model of interacting continua) showed the observed effect of increasing the stiffness of the fluid relative to the skeleton and striking similarities on the basis of partly estimated parameters. In fact guided by the calculations, the dips were identified as reflections.
However, for the reported series of experiments the total set of the parameters for the model are not yet available (due to the limited character of the project so far) in order to come to a detailed comparison between time histories at certain locations in the model and in the experiment at this moment.

## CONCLUSIONS AND RECOMMENDATIONS

From the results of our shock tube experiments at this stage we can conclude that:

1. The shock tube is a useful instrument to study pore pressure propagation in porous media due to its capability of generating a simple and reproducible loading form, which is helpful for testing theories.
2. The employed gauges have satisfactory properties with respect to linearity, hysteresis and frequency response in the range of interest (rise time >10μsec, pressure step $\leqslant$ 200 kPa.)
3. A definite "two-wave" structure has been identified from the recordings of the pressure gauges and the total pressure gauge. Furthermore we identified some of the effects of increasing the saturation degree.

Now the pressure gauges and the total pressure gauge generated interesting results, it seems justified to refine the set up and measure other variables and parameters in order to explore correlation with existing and extended theories. One candidate would be the strain in the skeleton. Further work should also be performed on the effect of air bubbles within the porous media with respect to wave phenomena. The work of Koning (1963) and Barends (1979) might serve as a starting point in order to quantify the effects of nonlinearity and damping as illustrated by Van der Kogel (1980). Work on these lines is pursued at the moment.

## ACKNOWLEDGEMENT

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