A practical method for extrapolating ambient pore pressures from incomplete pore pressure dissipation tests conducted in fine grained soils

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ABSTRACT: The estimation of ambient pore water pressures in an existing soil stratum for use in developing appropriate pore pressure distributions for input to various geotechnical engineering analyses often presents the engineer with challenges in locations devoid of sufficient piezometer coverage. One method of obtaining pore pressure data is by utilizing Pore Pressure Dissipation (PPD) testing conducted during cone penetration tests (CPTs). If the CPT advancement is paused for a sufficiently long time, the excess pore pressures generated during probe advancement decay to ambient levels. This stabilization of pore pressures can be exceedingly lengthy in actual practice if the existing stratum consists of a very low permeability soil. Often, PPD tests are terminated prior to the test reaching equilibrium which may result in misleading inputs to subsequent geotechnical analyses if the data is used without appropriate corrections. Based on equations presented by Mayne (2002) describing the decay of excess pore pressure during a pore pressure dissipation test, a technique for predicting ambient pore pressures from incomplete PPD data has been developed utilizing the solver function in Microsoft® Excel, and is presented herein.

1 INTRODUCTION

The majority of analyses performed by geotechnical engineers are sensitive to the characterization of effective stresses within the modelled soil stratum. Among other parameters and properties, an accurate characterization of effective stresses is dependent on an accurate characterization of pore water pressures within the soil.

The estimation of existing pore water pressure can be conducted using a variety of methods. Finite element seepage modelling can be used; however, the results are dependent on accurate input parameters and boundary conditions, which are often estimated and may be inexact. If sufficient piezometer coverage exists, a geotechnical engineer will often interpolate between piezometers in order to estimate a pore pressure distribution for input to various analyses.

In soils sufficiently loose or soft enough to allow for advancement of a cone penetrometer, Cone Penetration Testing (CPT) is often conducted to assist the engineer in characterizing in-situ material properties and site conditions. During a CPT, an electronic cone penetrometer is hydraulically pushed into the soil strata at a constant rate. Measurements are made of the resistance at the tip of the cone, the resistance along the shaft, and the pore pressure is monitored with a transducer as the cone is advanced. These measurements are used with appropriate correlations to estimate various engineering characteristics and in-situ conditions.

During CPT probe advancement in saturated soils, penetration pore pressures are recorded continuously. However, pore pressures observed as the probe is advancing are normally higher or lower than the ambient values due to excess pore pressures (positive or negative) due to contraction or dilation of the material. During the course of CPT testing, probe advancement can be periodically interrupted to conduct Pore Pressure Dissipation (PPD) tests. PPD tests allow for the measured pore pressures to equilibrate to their ambient values. These values can then be used to develop pore pressure profiles within the material.

The amount of time required for the excess pore pressures to dissipate to equilibrium in a PPD test is dependent on the hydraulic conductivity and consolidation characteristics of the soil. The excess pore pressures generated during CPT in a highly permeable soil will dissipate almost immediately. On the other end of the spectrum, the excess pore pressures generated during a CPT in a low permeability silt or clay could take several hours or even days to dissipate. This could make the characterization of ambient pore pressure conditions in these types of materials using PPD testing extremely time consuming, expensive and impractical. If the PPD test is terminated prior to reaching equilibrium, this could lead to an incorrect characterization of ambient pore pressures if the final pore pressure measurements are incorporated into geotechnical interpretations without appropriately correcting for the fact that the ambient pore pressure has not been reached, as some excess pore pressures are still being measured at the incomplete conclusion of the PPD test.

2 PORE PRESSURE DISSIPATION TEST FORMULATION

When a cone penetrometer is advanced in a saturated soil, excess pore pressures are induced due to two different mechanisms. Positive pore pressures immediately develop due to a reduction in volume caused by the advancement of the probe itself. In addition, either positive or negative pore pressures are induced due to shearing of the soil. If the soil is relatively dense, shearing will produce a negative pore water pressure response, and if the soil is relatively loose, shearing will produce a positive pore water pressure response. Except in the case of extremely dense soils, the positive pore pressures induced by probe advancement will control the initial response. This will be observed by a net positive excess pore pressure that will decrease with time during a PPD test.

After the advancement of the probe ceases and the PPD test is commenced, the excess pore pressures induced by both mechanisms will begin to dissipate with time. P.W. Mayne (2002) presents an approximate closed form series of equations to describe the excess pore pressures due to volumetric and shear strains at any time (t) during a PPD test. The series of equations presented in Mayne (2002) are approximations developed based on a rigorous solution presented by Burns and Mayne (1998).

According to the formulation, the total excess pore water pressures at any time t during a PPD test is given by:

$$\Delta u_t = (\Delta u_{vol})_i\,[1+50T']^{-1} + (\Delta u_{shear})_i\,[1+5000T']^{-1} \tag{1}$$

where:

$$(\Delta u_{vol})_i = \sigma'_{vo}\left(\frac{2M}{3}\right)\left(\frac{OCR}{2}\right)^{\Lambda}\ln(I_R) \tag{2}$$

$$(\Delta u_{shear})_i = \sigma'_{vo}\left[1-\left(\frac{OCR}{2}\right)^{\Lambda}\right] \tag{3}$$

$$T' = (c_h t)/(a^2 {I_R}^{0.75}) \tag{4}$$

$$M = \frac{6\sin(\phi')}{3-\sin(\phi')} \tag{5}$$

$$I_R = rigidity\ index = G/S_u \tag{6}$$

$$\Lambda = plastic\ volumetric\ strain\ ratio = 1\text{-}C_S/C_C \tag{7}$$

$$\sigma'_{vo} = vertical\ effective\ stress = (\gamma * z) - u_0 \tag{8}$$

and:

$\gamma = the\ in\ situ\ unit\ weight\ of\ the\ soil\ being\ tested$
$z = the\ depth\ of\ the\ PPD\ test$
$u_0 = the\ ambient\ pore\ water\ pressure$
$G = shear\ modulus\ of\ the\ soil\ being\ tested$
$S_u = undrained\ shear\ strength\ of\ the\ soil\ being\ tested$
$C_h = coefficient\ of\ horizontal\ consolidation$
$a = the\ radius\ of\ the\ cone\ penetrometer$
$OCR = overconsolidation\ ratio$
$C_S = swelling\ index$
$C_C = coefficient\ of\ compression$
$\phi' = the\ effective\ stress\ friction\ angle\ of\ the\ soil\ being\ tested$

It is of note that $(\Delta u_{vol})_i$ is the initial excess pore pressure induced by the immediate reduction in volume due to the advancement of the cone penetrometer and $(\Delta u_{shear})_i$ is the initial excess pore pressure induced by the shearing response. $(\Delta u_{vol})_i$ is always positive because it is induced by the immediate volumetric strains caused by advancement of the cone penetrometer. Conversely, $(\Delta u_{shear})_i$ can be either positive or negative depending on the relative density of the in-situ soil.

A relatively dense soil (with an OCR greater than approximately 2) will exhibit a dilatory response to shearing, increasing the volume of the voids on the shearing plane resulting in negative shearing induced excess pore pressures. A loose soil (with an OCR less than approximately 2) will exhibit a contractive response to shearing, decreasing in volume on the shearing plane and resulting in positive shearing induced excess pore pressures. A soil with an OCR approximately equal to 2 will exhibit a pore pressure neutral response to shearing.

The total measured pore pressure at any time (t) during a test is a sum of the ambient pore water pressure (u_0) and the excess pore pressures due to initial volumetric strains and shear strains as follows.

$$u(t) = u_0 + \Delta u_t \tag{9}$$

It is of note that u_0 is constant, while Δu_t will decay with time. Thus, at t = large, the measured pore pressure will trend towards the ambient pore pressure.

3 SPREADSHEET EXTRAPOLATION METHOD

When a PPD test is terminated at a t before $u(t) \cong u_0$, the mathematical formulation presented in Section 2 can be fit to the available data using the solver function in Microsoft Excel and extrapolated to t = large. The extrapolated curve will asymptotically approach u_0.

The first step in setting up a spreadsheet to do this is to designate several cells within the spreadsheet that correspond with uncalculated input parameters. The uncalculated inputs include the following: γ, z, u_0, G, S_u, C_h, a, OCR, C_s, C_c, and ϕ'.

With adequate laboratory and in-situ materials testing, all of the parameters noted above can be obtained or estimated except for the ambient pore water pressure, u_0. This level of soil characterization is rarely completed in practice, and as such, many of the uncalculated inputs may be unknown.

Due to the high number of variables, the most practical means of solving Mayne's formulae is to use an approach that results in the best curve-fitting by establishing estimated parameters that produce the best correlation between the experimental data and the modelled curve. Since the ultimate goal is to match the available data with a "best fit" curve, allowing for the variation of more than one of the above inputs will likely yield a better fit to the partial PPD test data. After the appropriate cells within the spreadsheet are designated, actual values can be entered in if they are known. For unknown values, an initial reasonable assumption should be entered which will be varied later to fit the mathematical formulation to the PPD test data.

The next step is to designate cells which will contain the input parameters that are calculated but not time dependent. These cells should include formulae to calculate the appropriate parameters based on the uncalculated inputs noted above. The non-time dependent calculated values include the following: $(\Delta u_{vol})_i, (\Delta u_{shear})_i\ M, I_R$, Λ, and σ'_{vo}. These values can be calculated using equations 2, 3, 5, 6, 7, and 8 respectively.

Next, 6 columns should be designated to calculate time-dependent calculated values. The first column should be labeled as time (t). Time elapsed during the PPD test should be entered into this column at the same intervals that measurements were taken during the PPD test. The second column should contain the modified time factor T', which should be calculated at each time interval based on Equation 4. The third column should contain Δu_t, or the time dependent total excess pore water pressure, which should be calculated at each time interval based on Equation 1. The fourth column should contain the calculated time-dependent total pore water pressure $u(t)$ at each time interval, which should be calculated using equation 9. The fifth column should contain the measured data from the PPD test at each time interval. The sixth column should contain the difference between columns 4 and 5 raised to the power of 2 at each time interval.

Next, a cell should be designated that contains the sum of all the values in column 6. In order to fit the mathematical formulation to the measured PPD test data, the sum of the values in column 6 needs to be minimized. This is done using the solver function, which is an add-in for Excel available directly from Microsoft. Within the solver dialog box is an input box labeled "Set Objective". The objective should be set to the cell that contains the sum of the values in column 6. The objective should be set to min. The input box labeled "by changing variable cells" can contain any number of the unknown uncalculated inputs noted above, and must include u_0.

When the solve button is clicked, Excel will attempt to fit the formulation to the measured data by minimizing the difference between the measured curve and calculated curve, by changing the designated variables. The final value of u_0 after pressing "solve" is the modelled ambient pore water pressure value. The appropriateness of the fit can be inspected by plotting the calculated time-dependent pore pressure $u(t)$ together with the measured values from the PPD test over time.

If the fit to the field data is deemed unacceptable, or the solver function is unable to find a solution, the following steps can be taken to improve the fit:

1. Modify the initial assumption for the uncalculated input parameters to improve the fit manually prior to using the solver function to refine the fit;
2. Allow for more of the uncalculated input parameters to be variable to generate a better fit; and
3. Eliminate the first few measured PPD test readings from the regression calculations, i.e., don't include their column 6 values in the sum of the squared differences that is minimized using the solver function. Since excess pore pressures often decrease very rapidly from a very high value in the first few seconds of a PPD test, including the first few readings may create computational complexities for the software.

4 VALIDATION OF THE EXTRAPOLATION METHOD

The above method has been utilized by the author in order to extrapolate ambient pore water pressure values from PPD tests conducted within a Tailings Storage Facility containing fine-grained, low permeability tailings. In general, the PPD tests were allowed to dissipate for approximately 1 hour before they were terminated due to time constraints. Data from several of the incomplete PPD tests along with appropriate extrapolations developed using the method described in Section 3 are shown on Figure 1.

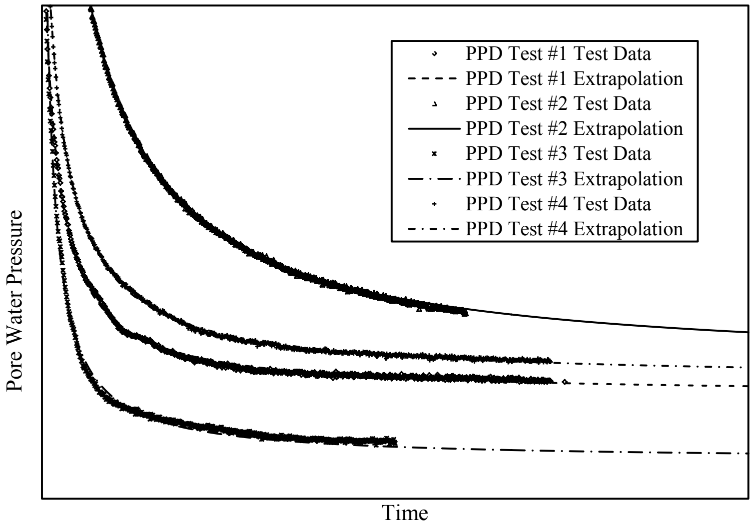

Figure 1. Extrapolations of Incomplete PPD Tests
Shown With Experimental Test Data

As shown on Figure 1, the extrapolation regressions closely reflect the test data for the PPD tests shown, indicating that the method described in Section 3 models the experimental data relatively well. The shapes of the extrapolated curves past the available test data sets appear to extend naturally, asymptotically approaching the respective values of u_0 indicating that the extrapolations and calculated values of u_0 are likely appropriate.

In order to further investigate the appropriateness of the extrapolated curves developed using the method described in Section 3, two separate PPD tests that were originally run nearly to completion ($u(t) \cong u_0$) were artificially truncated to investigate how closely fits developed using truncated datasets matched the actual data that had been truncated.

The first PPD test, herein denoted as Test A was originally run to t=3600 seconds. The measured pore water pressure at the conclusion of the test was approximately 25.1 meters of hydraulic head. A curve fit was developed using the full dataset in order to get a baseline fit based on the method described in Section 3. The test data was then truncated to t= 3000 seconds, t=2000 seconds, t=1000 seconds, t=500 seconds, and t=250 seconds. Extrapolations were then developed to fit the truncated data sets. The full set of experimental data is plotted together with the extrapolated curve fits developed using the full data set and the various truncated data sets on Figure 2.

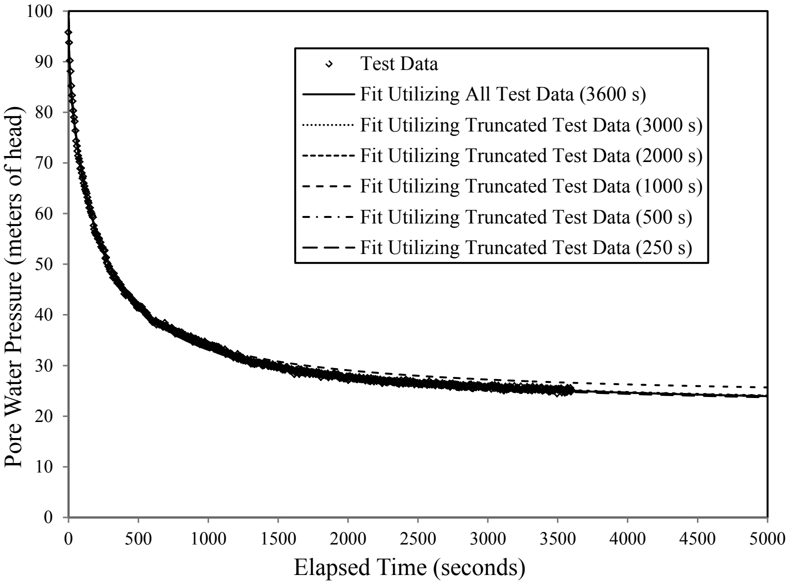

Figure 2. Extrapolations of PPD Test A Developed
Utilizing Various Truncations of Experimental Data

The u_0 value from the curve developed using the full data set was estimated to be 21.1 meters of hydraulic head. The u_0 values developed using the truncated data sets were estimated to be 21.0, 21.3, 23.2, 21.3, and 20.9 meters of hydraulic head for the extrapolations developed using t= 3000 seconds, t=2000 seconds, t=1000 seconds, t=500 seconds, and t=250 seconds of experimental data, respectively. Aside from the slight variation in the curve developed utilizing 1000 seconds of experimental data, the extrapolated curves shown on Figure 2 are indistinguishable from each other and fit the experimental data exceedingly well.

The slight difference in the predicted ambient pore pressure when the experimental data is truncated after 1000 seconds is due to an inconsistency in the experimental pore pressure decay curve that occurs between approximately 600 and 1000 seconds into the test. It is unknown why this small “blip” in the test data occurred. However, the shape of the decay curve normalized itself later in the test. This issue highlights the importance of obtaining as much experimental data as time and budget constraints allow in order for the development of the best possible extrapolation.

A second test run nearly to completion, herein denoted as Test B was originally run to t=950 seconds. The measured pore water pressure at the conclusion of the test was approximately 9.1 meters of hydraulic head. A curve fit was developed using the full experimental dataset in order to get a baseline regression. The test data was then truncated to t= 700 seconds, t=500 seconds, t=300 seconds, t=100 seconds, and t=50 seconds of experimental test data. Extrapolations were then developed using the truncated data sets. The full set of experimental data is plotted together with the extrapolated curve fits developed using the full data set and the various truncated data sets on Figure 3.

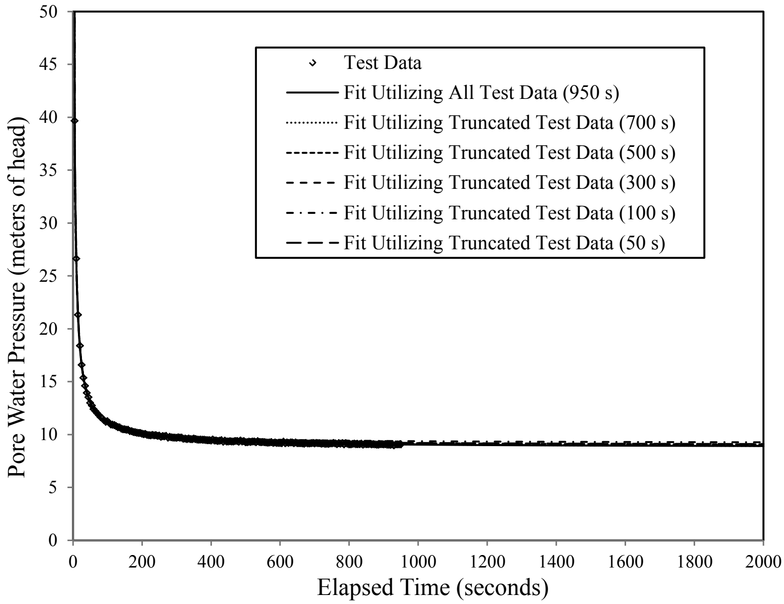

Figure 3. Extrapolations of PPD Test B Developed
Utilizing Various Truncations of Experimental Data

The u_0 value from the curve developed using the full data set was estimated to be 8.8 meters of hydraulic head. The u_0 values developed using the truncated data sets were estimated to be 8.8, 9.0, 8.8, 9.2, and 9.0 meters of hydraulic head for the curves developed using t= 700 seconds, t=500 seconds, t=300 seconds, t=100 seconds, and t=50 seconds, respectively. The extrapolated curves shown on Figure 3 all model the experimental data very well, and are virtually indistinguishable from each other.

The information presented on Figures 2 and 3 indicates that the extrapolation method presented in Section 3 is capable of predicting ambient pore pressure values and the final shapes of incomplete PPD curves reasonably well even using a dataset from a PPD test that is truncated well before completion of the test. Nevertheless, the ambient pore pressure values developed using this method are only estimates that generally will improve with an increasing duration of the test. Allowing a PPD test to run for as long as practical will smooth out potential experimental inconsistencies in the data, and allow for a better estimation of the ambient pore water pressure. In general, it is still recommended that PPD tests be run to completion ($u(t) \cong u_0$) when possible. If time and budget constraints do not allow for PPD tests in a particularly low permeability material to be run to completion, the tests should still be run as long as practical, and the method described in Section 3 can be used to provide reasonable estimations of ambient pore pressures.

5 CONCLUSIONS

This paper presents a practical method for extrapolating data collected from PPD tests terminated prior to completion in order to obtain estimates of ambient pore water pressures. When pore PPD tests are run in conjunction with CPTs in fine-grained soils, the amount of time required for the PPD test to reach completion can be lengthy. Often, budget or time constraints require the tests to be terminated prior to reaching a condition where 100% of excess pore water pressures generated during probe advancement have decayed. When the tests are terminated early, an extrapolation of the available test data is required to obtain ambient pore pressures for use in various geotechnical analyses.

The method presented herein utilizes equations presented by P.W. Mayne (2002) in conjunction with the solver function in Microsoft Excel to extrapolate incomplete PPD test results to completion in order to obtain ambient pore water pressure values. A validation of the model is provided using truncated PPD tests that were run nearly to completion to demonstrate the ability of the method described herein to predict the shape of the dissipation curves past the point of truncation. The results of the validation exercise indicate that the extrapolation method is capable of reasonably predicting the shape of PPD curves past the point of extrapolation and ambient pore water pressure values even when the curves are truncated well before completion of the PPD test, which is defined at the point where $(u(t) \cong u_0)$. It is still recommended that each PPD test be allowed to run for as long as possible because in general, more data will allow for the development of a more accurate extrapolation curve.

6 REFERENCES

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Mayne, P. W., 2002, *Flow Properties from Piezocone Dissipation Tests*, Georgia Tech University, Atlanta, Georgia, USA.