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Vertical Effective Stresses from Multi-Piezometer Array System (MPAS) Pore Pressure Measurements at the Coastal Oil-Spill Simulation Facility

Prepared by

Glen R. Andersen
S. Peter Gonzales

Texas Engineering Experiment Station
College Station, Texas

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Glen R. Andersen and S. Peter Gonzales

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332 Wisenbaken Engrg Research Center
College Station, TX 77843-3000

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13. ABSTRACT (*Maximum 200 words*)

This report describes and examines the excess pore water pressures generated in a sand bed subjected to gravity water waves as measured by piezometer probes of the Multi-Piezometer Array System (MPAS). Experiments were conducted in a medium-sized wave tank (2.1 m wide, 2.4 m deep, and 30 m long), floored by 1 m of uniform, saturated, medium dense to dense fine sand covered by 1.2 m of sea water. Two MPAS probes were embedded 0.30 m in the sand bed (with integral sensor and amplifier housing extending 0.68 m above the bed) and positioned 6.1 m apart. The first probe had a mass of 32 kg and was supported on the sand surface by a thin ring footing, whereas to the second probe steel angles were added beneath the ring footing to serve as shear keys and increasing the mass to 57 kg. Multiple trains of 60+ uniform waves were created with wave heights (trough to crest) up to 0.4 m and a wave period of 5 sec.

Excess pore water pressures measured by the MPAS probes were found to differ from theory in that changes in vertical effective stress in the sediments apparently are not tied with vertical total stress at the sediment/water interface, i.e., effective stresses are decreasing in the sediments when predicted total stresses are increasing, and vice versa. Also, large differences in measured excess pore water pressures were observed between the probe with thin ring footing and that with added steel angle weighting/shear keys, in similar total stress environments, indicating that factors other than changes in total stress, i.e., the probes, base configuration, and /or integral electronics housing, are influencing the measured pore water pressures.

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Prepared by:
Glen R. Andersen
formerly of
Texas A&M University
and
S. Peter Gonzales
formerly of
Texas A&M University

Prepared for:
Naval Research Laboratory
Marine Geosciences Division
Stennis Space Center, MS 39529-5004

EXECUTIVE SUMMARY

A set of experiments were performed at the Coastal Oil-Spill Simulation (COSS) facility in Corpus, Christi, Texas to investigate the behavior of the Multi-Piezometer Array System (MPAS) in a carefully-controlled uniform wave field. A medium-sized wave tank (2.1 m wide, 2.4 m deep, and 30 m long) was used to conduct the tests. Sand (uniform fine sand from a local lagoon) was placed as a sand test bed and used to form a beach. The sand in the test bed was saturated through hydraulic jetting and densified through vibro-compaction. The achieved densities were medium dense to dense as measured by drive cylinders after testing. Details of the sand bed placement and properties can be found in Gonzales (1999). Sea water from the local lagoon was used as the testing medium in the tanks.

Two MPAS probes, #3 and #11, were placed on the surface of a horizontal sand bed (approximately 1 m thick) and were separated by approximately 6.1 m longitudinally in the wave tank. Probe #3 was placed in the test bed with anchor feet "tie downs" composed of steel angles (6 x 100 x 150 mm) attached to the original probe foot and forming a box that surrounds the sensing shaft and penetrates into the sediments. Probe #11 was placed in the test bed with the original ring foot in a manner identical to the configuration used in the NATO Mine Burial Study Phase I in April/May 1997.

Multiple trains of 60+ uniform waves were created with a wave height (trough to crest) of approximately 0.4 m, a wave period of 5 sec, and a water depth of approximately 1.2 m. The wave field contained both incident waves from the wave maker and reflected waves from the beach. The response of the MPAS probes was recorded and analyzed. In their current configuration, the four porous stones are located on the sensing shaft, one just above the sediment/water interface, and the others at depths of 0.02 m, 0.12 m, and 0.22 m, respectively.

An analysis of the measured pore water pressures was performed using a time-averaging technique where the results from multiple identical waves in each train were combined (34 to 35 individual waves in the same wave train). The measured behavior from this time averaging scheme is considered to be representative of the actual performance of the MPAS in a wave tank that is simulating a near shore environment.

Changes in vertical effective stress in the marine sediments under the action of the uniform wave field have been inferred from the measured pore pressures and from changes in total stress derived from the measured bottom pressures using a Theory of Elasticity formulation and Terzaghi's effective stress equation.

Observations

An analysis of the water column and pore pressures measured at the MPAS probes led to the following observations:

1. A **decrease in vertical effective stress** in the sediments occurs at the probes near the sediment/water interface **under the crest** of the surface waves;
2. The **largest decrease in vertical effective stress** occurs at **0.12 m** below the sediment/water interface **under the trough** of the surface waves;
3. The probe with the heavy steel feet "tie downs" measured an **increase in vertical effective stress** at 0.22 m below the sediment/water interface **under the trough** of the surface waves;
4. While the calculated total stress distributions in the sediment (derived from the Theory of Elasticity and using the measured water column pressures) at the two MPAS probe locations were similar, the measured pore pressures were quite distinct, and thus factors other than the magnitude of the water column pressure at the sediment/water interface are potentially influencing the measured pore pressures.

Conclusions

Direct measurements of pore pressures in marine sediments in a uniform wave field under carefully controlled conditions have provided a benchmark for the performance of the MPAS probes. The measurement system of each probe is self-contained and provides an indication of the marine sediment behavior in the immediate vicinity of the probe shaft. The pore pressures measured by the MPAS probes are peculiar in the sense that measured changes in vertical effective stress in the sediments are apparently not tied with vertical total stress at the sediment/water interface (i.e., effective stresses are decreasing in the sediments when calculated total stresses are increasing and vice versa). Large differences in behavior were observed between probes with two different "footing" configurations but placed in similar total stress environments, thus indicating that factors other than changes in total stress are influencing the measured pore pressures.

Recommendations

The authors recommend that scientific and engineering principles be employed to explain the peculiar behavior of the MPAS probe measurements and that these principles be used to form an analytical technique for the interpretation of marine sediment pore pressures that will be measured by the MPAS probes in future deployments.

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INTRODUCTION

The following report presents the changes in vertical effective stress that can be inferred from pore pressures measured along the shafts of two Multi-Piezometer Array System (MPAS) probes, one with the original ring footing and another with an added heavy anchor skirt "tie-down" that penetrates the sediments. The tests described herein were conducted at the Coastal Oil-Spill Simulation (COSS) facility in Corpus Christi, Texas in October and November of 1998 under the supervision of Dr. Glen R. Andersen, Assistant Professor, Texas A&M University during the field work. This series of tests represented a second round of pore pressure measurements at COSS and hence are referred to herein as COSS 2. The tests were conducted in a medium-sized (2.1 x 2.4 x 30 m) wave tank using a natural lagoon sand found near the test facility. A complete description of the COSS facility and the sand properties and placement techniques is presented by Gonzales (1999).

The MPAS probes (#3 and #11) were placed on a horizontal sand bed separated by approximately 6.1 m and were subjected to four uniform regular wave trains of (60 waves each) with a 5.0 sec period and a wave height of approximately 0.4 m and a water depth of approximately 1.2 m. The wave field consisted of both incident and reflected waves. The analysis presented herein represents time averages of multiple identical waves (34 to 36 wave forms for each data point) in one of the four wave trains (Wave Train #3) that were triggered during the testing program. These results are representative of the general behavior observed in the other four wave trains.

The sand used as the test bed was saturated using hydraulic jetting with a 76 mm diameter nozzle and a flow rate of 110 liters per min (300 gallons per min) of fresh seawater drawn from the nearby lagoon. The sand had been previously placed in the wave tank and the water level was increased to cover the top of sand. Hydraulic jetting systematically resuspended all of the sand grains in the water column and allowed them to resettle while being entirely immersed in the seawater. The jetting was accomplished in a systematic manner so that all sand in the test bed was resuspended and resettled as just described. After saturation, the sand was densified throughout its depth (approximately 1 m) using a vibrating concrete torpedo on 0.3 m centers. The resulting density of the test bed was considered to be medium dense to dense. Details of the measured densities are presented by Gonzales (1999).

Details about the individual MPAS probes and the data acquisition system can be found in Andersen et al. (1998). The theory and operation of the MPAS probes can be found in Andersen et al. (1997).

ANALYTICAL TECHNIQUE

Theory Applied

Measurements of changes in pore water pressure in shallow marine sediments do not give a direct measure of changes in effective stress. However, these measurements can be used to infer changes in effective stress through the use of simplified analytical tools from the Theory of Elasticity and Terzaghi's Effective Stress Equation. Poulos and Davis (1974) present an extensive treatment of the application of the Theory of Elasticity to the prediction of changes in stresses within a sediment mass. Figure 1 presents the equation and geometrical considerations for a prediction of changes in vertical stress within a sediment mass under the action of an infinite line load applied at the surface. The vertical stress (σ_v) at any point in the sediment mass can be expressed as:

$$\sigma_v = \frac{2Pz^3}{\pi\left(x^2 + z^2\right)^2} \tag{1}$$

where P is the intensity of the line load (force/unit length); z is the depth below the surface of the sediments; and x is the horizontal position from the point of load application on the surface. Note that according to Eq. (1) the vertical stress is independent of the soil material properties. As such, vertical total stresses from the Theory of Elasticity are routinely used with confidence in geotechnical engineering calculations and have been demonstrated to have surprisingly good agreement with actual measured pressures even where highly nonlinear plastic behavior is expected (Lambe and Whitman, 1969).

The infinite line load solution can be integrated to estimate the vertical stresses under an arbitrarily shaped surface load. Considering the line load as a strip with an intensity of u (force per unit area) and a width, dx, an integral can be developed. Figure 1 presents the geometrical considerations and the resulting integral that can be evaluated by numerical integration to estimate the resulting vertical stress at some depth z and some position x in the sediment. This integral is:

$$\sigma_v = \int_{-\infty}^{+\infty} \frac{2z^3u}{\pi\left(x^2 + z^2\right)^2}\,dx \tag{2}$$

where all terms have been previously defined. The effect of a surface wave on the sediment/water interface is to cause a change in total stress and hence Eq. (2) can be used to estimate the corresponding changes in total stress within the sediments. Note that the preceding equations are both based on a two dimensional analysis, and hence the analysis presented in this report is strictly applicable to 2-D wave trains or wave regimes under which the third dimension can be neglected.

Note that according to Eq. (2), for shallow depths in the sediments ($z \rightarrow 0$), the stress conditions at the surface some large distance x from the analysis point (x,z) will have very little influence on the resulting vertical stress. The practical implication of this statement is that it is not necessary to consider the entire surface wave form in order to get a reasonable estimate for the corresponding changes in vertical total stress near the sediment/water column interface. In other words, only a portion of the wave form is necessary to obtain a good estimate of vertical stress for a shallow analytical depth, z.

Changes in vertical total stress from Eq. (2) are due only to changes in total stress at the sediment/water interface, and thus they do not include any shear stresses that may be present due to the orbital velocities of the water particles in the water column. Such an assumption has been used routinely by modelers attempting to predict pore water pressures in marine sediments.

Terzaghi's effective stress equation describes a very definite relationship between the vertical total stress (σ_v), the vertical effective stress (σ'_v), and the pore water pressure (u) of the form:

$$\sigma'_v = \sigma_v - u \tag{3}$$

Equation (3) has been demonstrated to be valid over a wide range of soils under fully saturated conditions. Changes in vertical effective stress in marine sediments can be determined from Eq. (3) by comparing changes in total stress [as predicted by Eq. (2)] to measured pore pressures from the MPAS probes. Figure 2 presents a plot of calculated changes in total stress in the sediments from the wave form measured at the MPAS #3 location in the COSS 2 experiments as a function of depth in the sediments. If measured pore pressures fall to the right of the "Change in Total Stress" line, there is a decrease in vertical effective stress. Conversely, if the measured pore pressures plot to the left of the "Change in Total Stress" line, there is an increase in effective stress. The analysis presented in Fig. 2 is a strong tool to investigate measured pore pressure behavior and the associated changes in vertical effective stress.

Total Stress.exe

A Visual Basic 6.0 program for Windows 95/98 has been developed to evaluate the integral in Eq. (2) for any arbitrary 2-D wave form at any position in the soil mass. A listing of the code is presented in the Appendix along with a sample input file for the calculation. In order to use the program (Total Stress.exe), an input data file must be prepared in accordance with the sample input file. The user must provide measured or estimated changes in bottom pressure (at the sediment/water interface) along with the wave period (the program assumes uniform waves). The user must also provide the wave height and the time between successive data points. Up to fifty data points can be placed into the bottom pressure array. The user selects a portion of the measured water pressure time history with the central data point corresponding to the horizontal position of the desired point in the sediments (i.e., the time history will be an odd number of data points with the central point corresponding to x = 0 in the analysis). The user also selects the depths for which the resulting change in total stress is desired. Up to fifty depths can be selected for each run. After calculating the results, the user selects a new data file to store the input data and calculated results.

The user can experiment with the number of data points for the measured water pressure that are necessary to develop a reasonable approximation for the changes in total stress. The user can select one set of data points and compute the results and then either increase or decrease the number of data points and compare the predicted changes in total stress to see how much of a difference there is. If the difference between the two computations is tolerably small, then the number of data points is deemed sufficient. For the analysis presented herein, the authors selected 11 data points which roughly correspond to a 2.1 m segment of the wave form. The maximum depth below the sediment surface for this analysis is 0.24 m, and the accuracy of the integration is deemed sufficient for the conclusions developed herein.

ANALYSIS OF RESULTS

Uniform Wave Field

The wave maker at the COSS facility is capable of generating a train of uniform regular waves with a period of 5 sec and a wave height of 0.4 m. Figure 3 presents the initial time histories for the water column pressures near the sediment surface measured by MPAS Probes #3 and #11 for the third wave train. In the testing configuration, Probe #3 with the heavy metal anchor feet "tie-down" was located closest to the beach. Note that in Fig. 3 the initial wave forms are almost identical at both locations (the time scale has been offset to facilitate a direct comparison). After the second wave, deviations in the pressure from the two waves become more pronounced as the waves reflected from the beach interfere with those developed by the wave maker. Note that the trough at Probe #3 is decreased and the crest at Probe #11 is widened slightly.

The authors noted that stability in the wave form at each location was achieved after the first several cycles of the wave trains. In the subsequent analyses, only the stable portion of the wave trains with identical wave forms (34 to 35 waves) were considered.

Although the actual pressure wave forms at the two testing locations were distinct because of the reflected wave effects, an analysis of the total stresses in the sediments due to the measured total stresses at the sediment/water interface showed distinct similarities. Figure 4 presents this comparison. Note that the general shape of the attenuation curves (changes in stress as a function of depth) is the same at the two locations. The attenuation curves are offset due to differences in the magnitude of the crest and trough amplitudes as previously explained. If the measured pore pressures are predominantly a function of the total stresses at the sediment/water interface, then Fig. 4 would indicate that the pore pressure attenuation curves at the two locations would have approximately the same shape.

Time Averaging Technique

In order to develop a representative description of the behavior of the measured pore pressure data, a time averaging technique was employed. The measured peak crest pressures and peak trough pressures for identical successive waves were averaged. For the wave train presented in this report, 34 to 35 such waves were used in the averaging. These waves were taken from the stable portion of the wave train. Thus, each data point representing a measured pore pressure or bottom pressure is the average of a minimum of 34 data points each of which represent the identical condition as it reoccurred during the wave train. Figures 5 and 6 present time histories from Probe #3 and #11, respectively, for several waves during the stable portion of the wave train to illustrate the repetitive nature of the stable wave forms that were used for the time averaging analysis.

Pressure Distributions

Measured pore pressures as a function of depth in the sediments are compared directly with changes in total stress (predicted from Elastic Theory) in Figs. 7-10 in accordance with the analysis described in Fig. 2. Recall that a measured pore water pressure that plots to the right of the predicted total stress curve implies a decrease in vertical effective stress and one that plots to the right implies an increase. Note that in all plots, the measured pore pressure at the sediment/water interface is equal to the predicted total stress by definition.

Considering Probe #3 with the heavy steel foot "tie-down", the measured pore pressure at 0.02 m below the sediment/water interface underneath the crest of a surface wave indicated a decrease in vertical effective stress. Refer to Fig. 7. At some depth between 0.02 m and 0.12 m there was a transition to an increase in vertical effective stress. The greatest increase in vertical effective stress was measured at 0.12 m below the sediment surface.

Considering Probe #11 with the original ring foot, there was a slight decrease in vertical effective stress measured at 0.02 m below the surface as the crest of the waves passed over. Refer to Fig. 8. Somewhere between 0.02 m and 0.02 m there was a transition from a decrease in vertical effective stress to an increase. The greatest increase in vertical effective stress occurred at 0.12 m below the surface.

Considering Probe #3 with the heavy steel foot "tie-down", the measured pore pressures underneath the wave trough indicated a decrease in vertical effective stress in the upper zone of the sediments with an increase in vertical effective stress in the lower portions of the sediments. Refer to Fig. 9. The transition between decreases and increases in vertical effective stress occurred somewhere between 0.12 m and 0.22 m.

Considering Probe #11 with the original ring foot, the measured pore pressures under the wave trough indicated a decrease in vertical effective stress throughout the measured volume with the largest decrease occurring at 0.12 m. Refer to Fig. 10. There was only a slight decrease in vertical effective stress measured at the 0.22 m depth.

Referring again to Fig. 4, although the total stress attenuation curves have a very similar shape (meaning that the total stresses at the interface have a similar effect on the changes in total stress in the sediment at each position and for both the crests and the troughs), the pore pressure attenuation curves are quite distinct. Refer again to Figs. 7-10. Probe #3 exhibited a much larger decrease in vertical effective stress near the sediment/water interface under the wave crests. Probe #11 exhibited the highest increase in vertical effective stress under the wave crest at a depth approximately ½ of that exhibited by Probe #3. Probe #3 measured an increase in vertical effective stress under the wave trough while Probe #11 measured only decreases.

SUMMARY

The behavior of the individual MPAS probes has been investigated in a medium-sized wave tank at the COSS facility in Corpus Christi, Texas. The probes were configured with "foot" designs that were used in the Phase I and Phase II NATO Mine Burial Study, namely with the original ring foot and with a heavy steel skirt referred to as a "tie-down". Uniform wave trains consisting of 60 regular waves with a period of 5 sec, a wave height of 0.4 m and in a water depth of 1.2 m were triggered. The resulting wave forms were uniform and consistent for a large portion of each wave train. These wave forms included both incident and reflected waves similar to what would be expected in a near shore environment. Time averaging of the results of stable wave forms (achieved after an initial set of waves in each train) was used to develop representative estimates of measured bottom pressures and pore pressures.

Changes in vertical effective stress were inferred from the measured pore pressures and estimated changes in total stress from elastic theory in a formulation that is independent of the material properties of the sediments. This analysis represents a simple yet powerful tool to study fundamental aspects of marine sediment behavior as implied by the MPAS probe measurements.

The measured pore pressure data exhibited some peculiarities, namely: 1) decreases in vertical effective stress at or near the sediment/water interface when the wave crest is passing over; 2) increases in vertical effective stress at 0.22 m below the sediment/water interface when the wave trough is passing over (for Probe #3 with heavy steel feet); 3) the largest decrease in vertical effective stress under the wave trough was measured at 0.12 m below the sediment/water interface; and 4) large differences in the measured pore pressure response between the two probes with different "foot" conditions for wave environments that generate very similar changes in total stress.

CONCLUSIONS

The experimental program described in this report represents a benchmarking of the performance of the MPAS probes in a carefully controlled and repeatable environment. Considering the vertical effective stresses that can be implied from the measured pore pressures and bottom pressures, the behavior of these measurements is peculiar in that decreases in vertical effective stresses occur near the sediment/water interface when the total pressures at that interface are at a positive maximum. Also, increases in vertical effective stresses occur in the sediments when the total stresses at the sediment/water interface are at a minimum. The behavior of the probes with different "foot" configurations is distinct in that for very similar total stress conditions, the measured pore pressures are quite variable. Therefore, factors other than the magnitude of the total stress at the sediment/water interface are influencing the pore pressures measured by the MPAS probes.

RECOMMENDATIONS

Considering the peculiar nature of the measured pore pressures in terms of the implied changes in vertical effective stress, the authors recommend that scientific and engineering principles be employed to explain the behavior of the probes for different "foot" conditions. Once having established the appropriate scientific and engineering principles, the authors recommend that an analytical tool be developed to interpret the marine sediment pore pressures that will be measured by future MPAS probe deployments.

ACKNOWLEDGEMENTS

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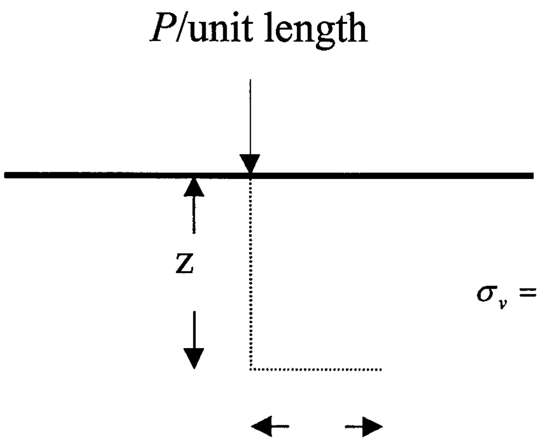
Lambe, T.W. and Whitman, R.V. (1969), Soil Mechanics, John Wiley and Sons, New York, NY, pg. 105.

Poulos, H.G. and Davis, E.H. (1974), Elastic Solutions for Soil and Rock Mechanics, John Wiley and Sons, New York.

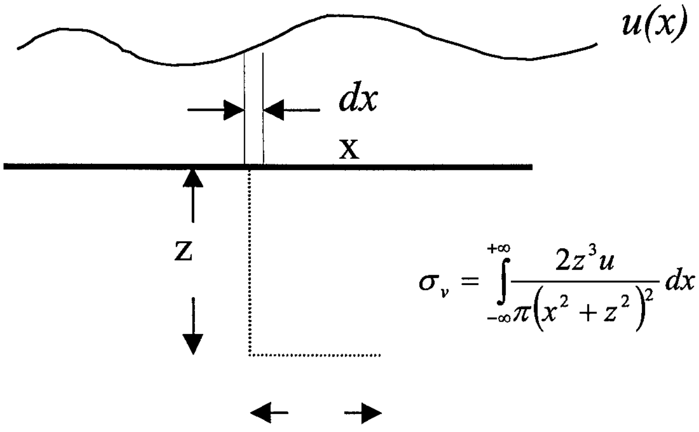
Figure 1 Elastic Solutions for Total Vertical Stress Under a Line Load and an Arbitrarily Shaped Load on the Surface of a Sediment Mass

Elastic Solution from Poulos and Davis (1974)



$$\sigma_v = \frac{2Pz^3}{\pi\left(x^2 + z^2\right)^2}$$

Elastic Solution for Arbitrary Shaped Surface Load



$$\sigma_v = \int_{-\infty}^{+\infty} \frac{2z^3 u}{\pi\left(x^2 + z^2\right)^2} dx$$

Figure 2 Changes in Vertical Effective Stress as Inferred from Changes in Calculated Total Stress and Measured Pore Water Pressures

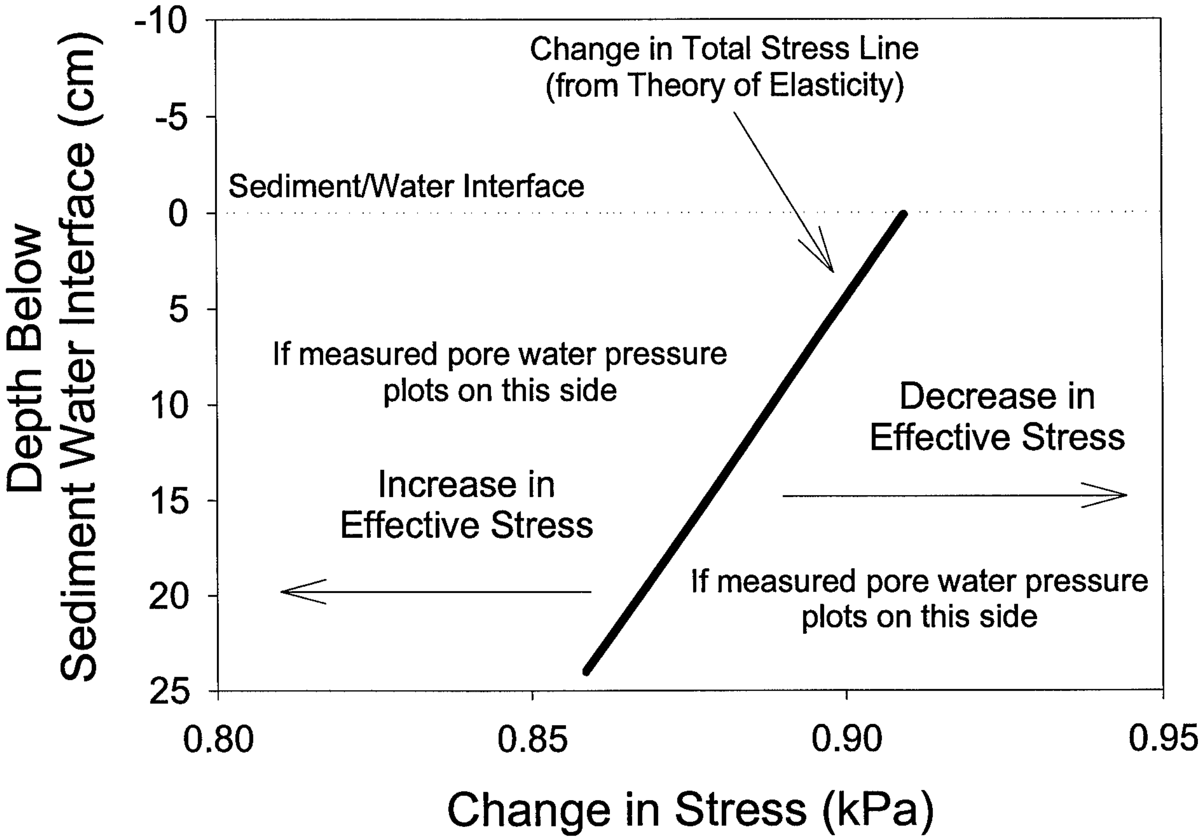


Figure 3 Comparison of Initial Pressures Near Sediment Surface at MPAS #3 and #11 Locations for COSS 2 Wave Train #3

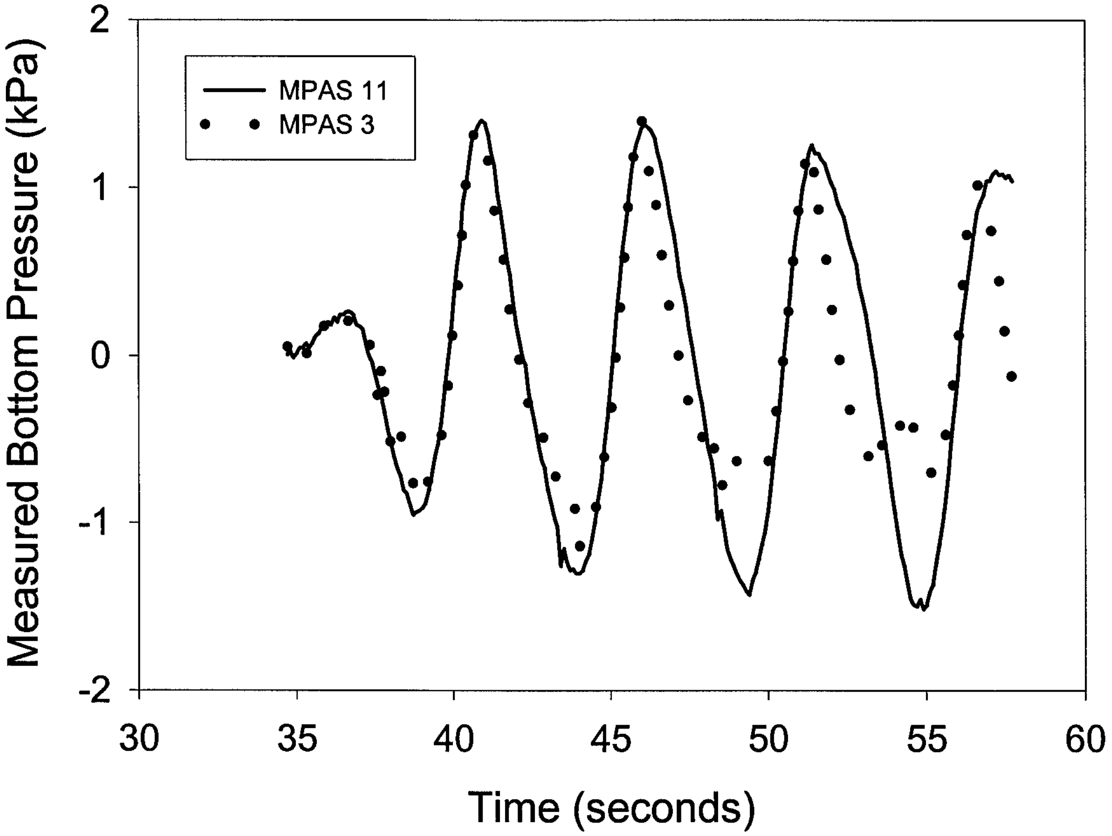


Figure 4 Comparison of Predicted Total Stresses at the Two MPAS Testing Locations

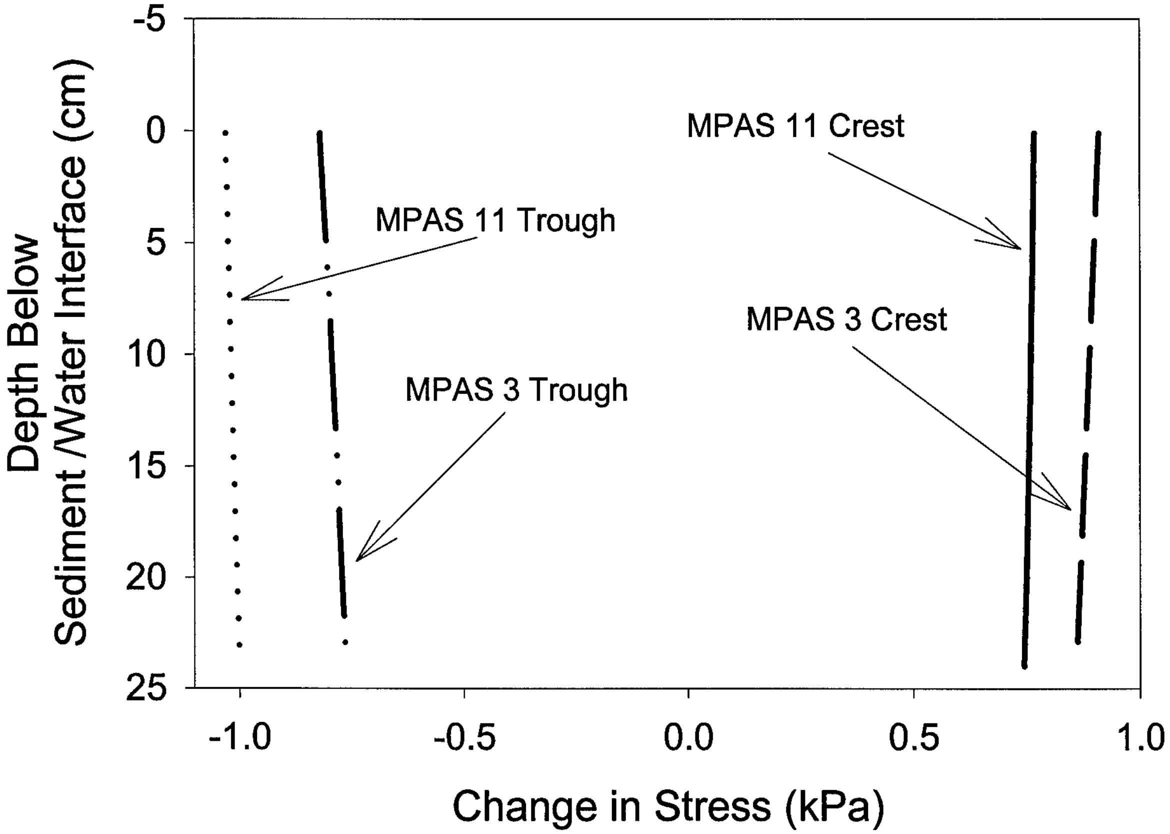


Figure 5 Bottom Pressure Time History for Several Uniform Waves for Probe #3

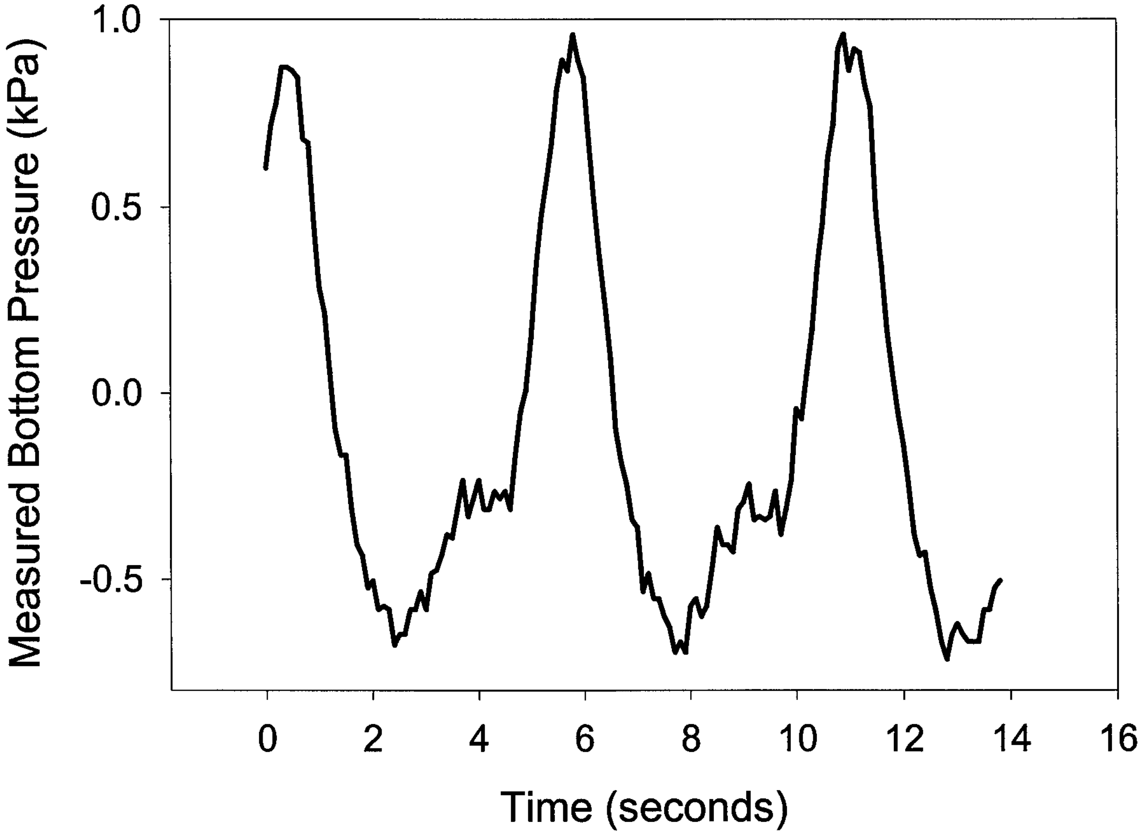


Figure 6 Bottom Pressure Time History for Several Uniform Waves for Probe #11

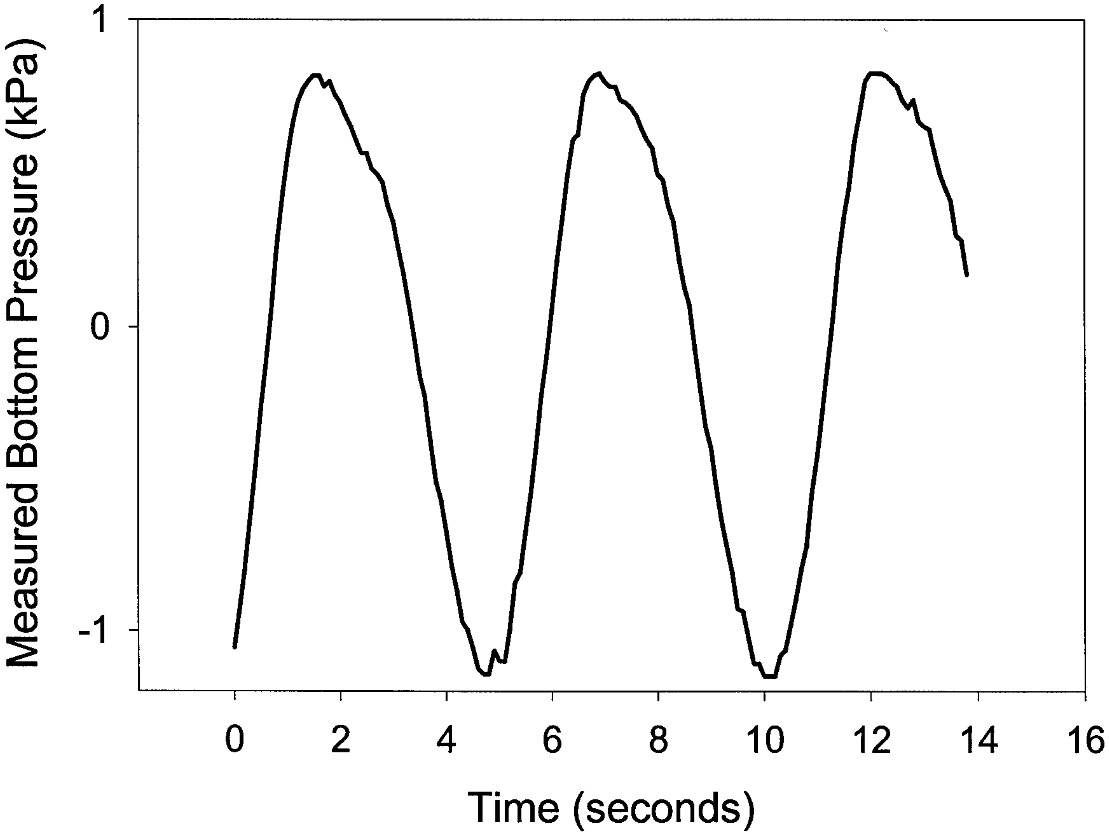


Figure 7 Implied Changes in Vertical Effective Stress Under Wave Crest for Probe #3 (with heavy, steel-angle base) Using an Average of 34 Uniform Waves

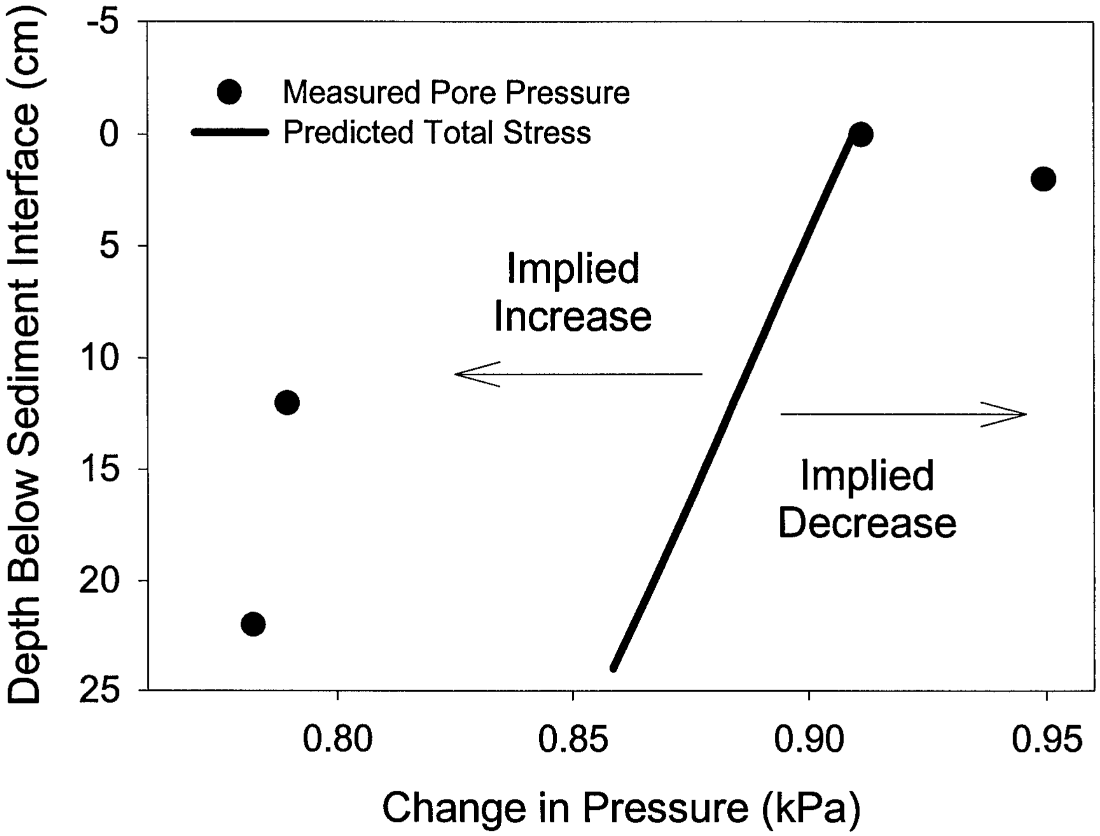


Figure 8 Implied Changes in Vertical Effective Stress Under the Wave Crest for Probe #11 (with light, ring base) Using an Average of 35 Uniform Waves

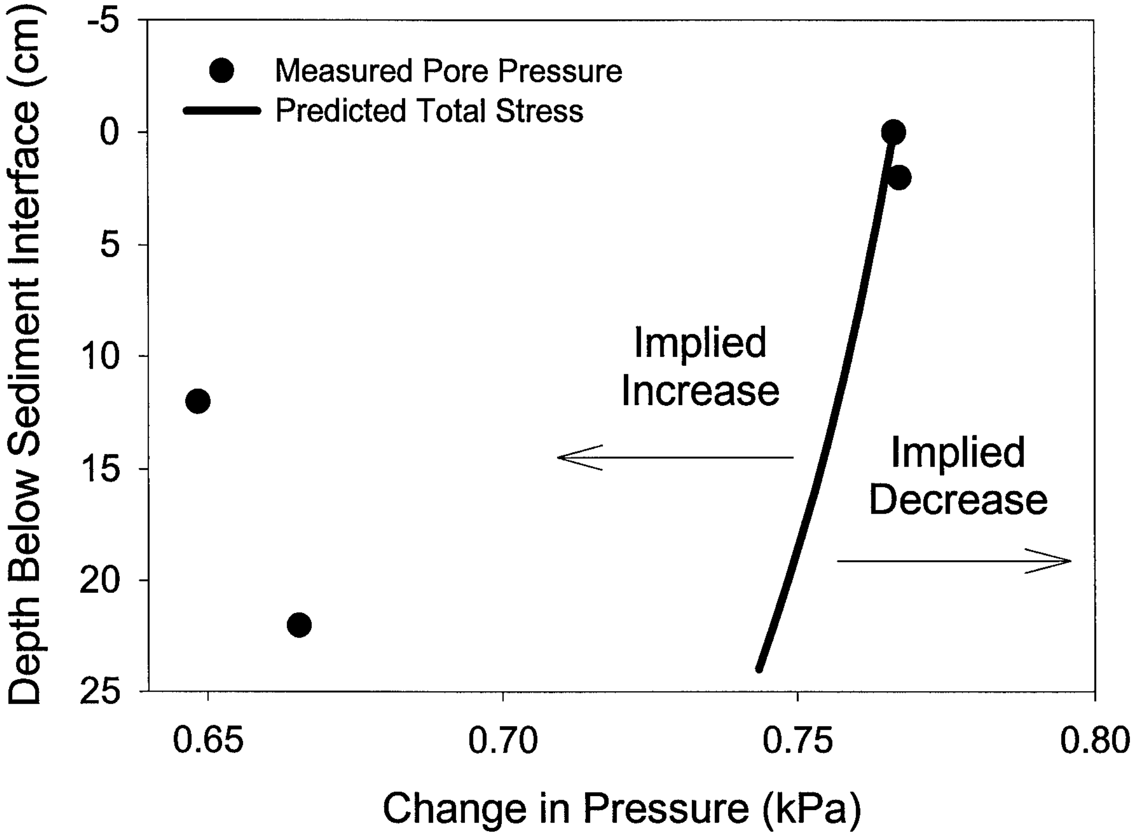


Figure 9 Implied Changes in Vertical Effective Stress Under Wave Trough for Probe #3 (with heavy, steel-angle base) Using an Average of 35 Uniform Waves

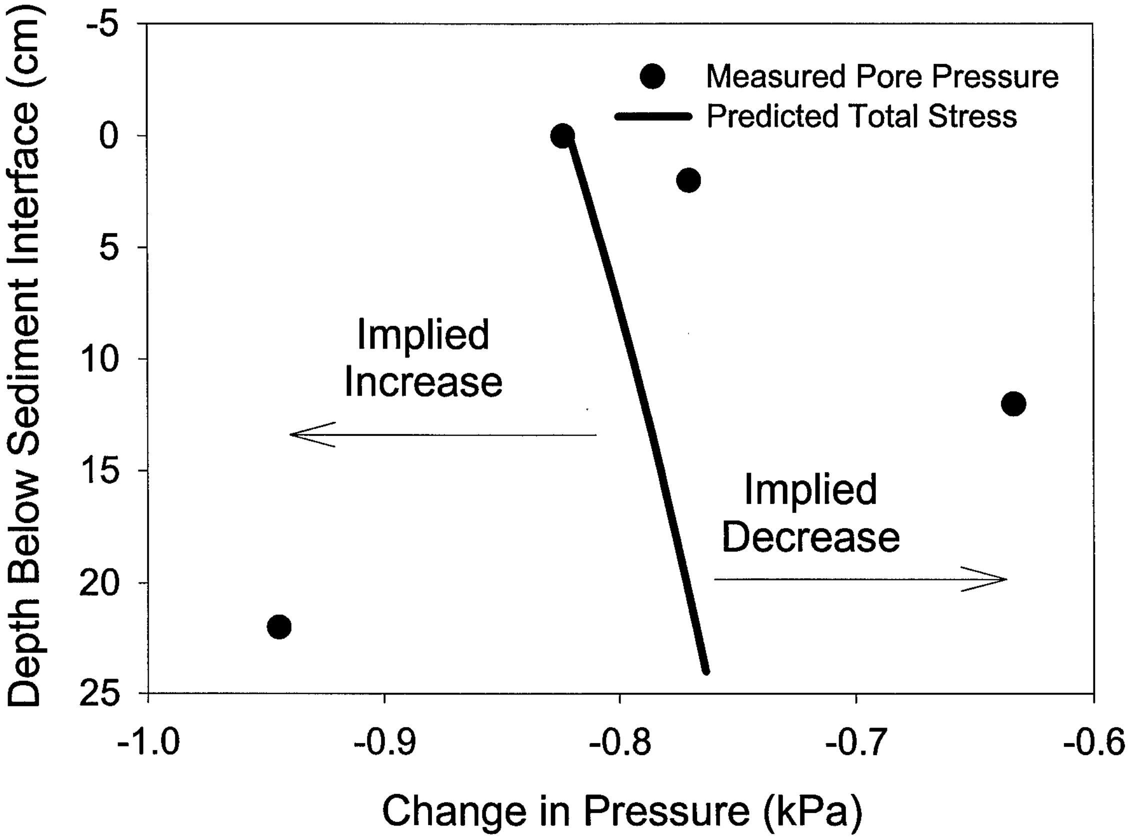
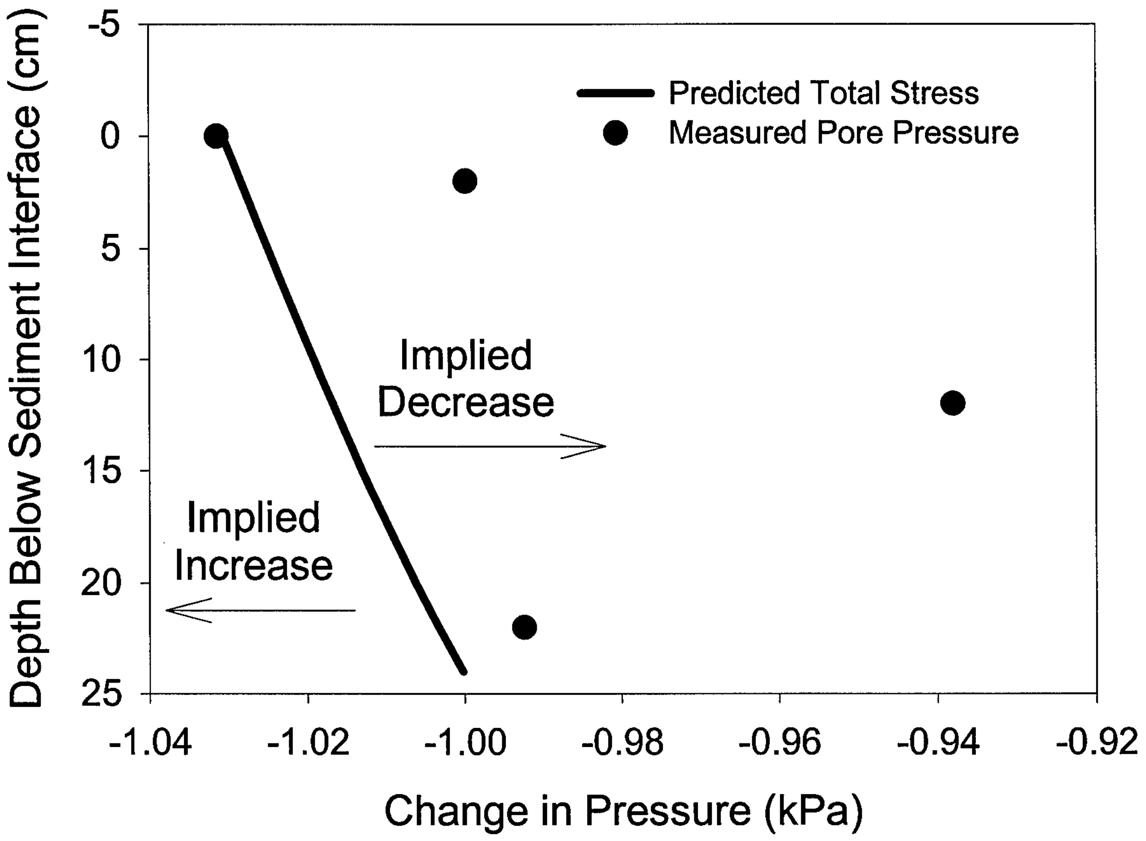


Figure 10 Implied Changes in Vertical Effective Stress Under Wave Trough for Probe #11 (with light, ring base only) Using an Average of 35 Uniform Waves



APPENDIX

Listing of Visual Basic Code for Total Stress.exe

```
Dim measwaterpress(50), depthofcalculation(50), calsigma(50)
Dim iflag1 As Boolean, iflag2 As Boolean, stepsize As Integer
Public txtline1, txtline2, txtline3, txtline4, txtline5, txtline6
Public txtline7, txtline8, txtline2a
Private Sub Form_Load()
iflag1 = False
iflag2 = False
End Sub
Private Sub mnuCalculate_Click()
If iflag1 = False Then
txtmessage = "Data must be input before calculation begins"
Else
txtmessage = "System Messages"
wavelength = 1#

' Estimate the wavelength from the waveperiod and waveheight

Call calwavelength(waveperiod, waveheight, wavelength)

   ' Compute the horiztonal distance between consecutive data points

deltax = wavelength * deltat / waveperiod

   ' Compute the number of data points to the left of the center point

npoints = Int((ndatapoints - 1) / 2)

' Integrate the pressure distribution using the Elastic Theory Equation
' Perform integration for each calculation point

For j = 1 To ncalpoints
   calsigma(j) = 0
   CXL = -deltax * npoints
   For i = 1 To (ndatapoints - 1)
      calsigma(j) = sigma + calsigma(j)
      sigma = 0
      CUL = measwaterpress(i)
      CUR = measwaterpress(i + 1)
      CXR = CXL + deltax
      Call intpress(CXL, CXR, CUL, CUR, depthofcalculation(j), stepsize, sigma)
      CXL = CXL + deltax
   Next i
   Combo3.AddItem calsigma(j)
Next j
iflag2 = True
End If
End Sub
```

```
Private Sub mnuExit_Click()
End
End Sub

Private Sub mnuNext_Click()
If iflag1 = False Then
txtmessage = "Select new file using the Open button on the Menu"
Else
For i = 1 To ndatapoints
   Combo1.RemoveItem (0)
Next i
For i = 1 To ncalpoints
   Combo2.RemoveItem (0)
Next i
txtmessage = "Now use the Open button to select the next file"
End If
If iflag2 = True Then
For i = 1 To ncalpoints
   Combo3.RemoveItem (0)
Next i
End If
End Sub

Private Sub mnuOpen_Click()
txtmessage = "System Messages"
txtReturn = ""
' Show the Open Dialog Box'

CommonDialog1.ShowOpen

' Display the name of the file selected'
txtReturn = CommonDialog1.Filename

'open file as a new object and read the first line

Dim fso As New FileSystemObject, ts As TextStream
Set ts = fso.OpenTextFile(CommonDialog1.Filename, ForReading)
txtline1 = ts.ReadLine
waveperiod = ts.ReadLine
txtline2 = ts.ReadLine
waterdepth = ts.ReadLine
txtline2a = ts.ReadLine
waveheight = ts.ReadLine
txtline3 = ts.ReadLine
deltat = ts.ReadLine
txtline4 = ts.ReadLine
ndatapoints = ts.ReadLine
txtline5 = ts.ReadLine

For i = 1 To ndatapoints
      measwaterpress(i) = ts.ReadLine
      Combo1.AddItem measwaterpress(i)
Next i
```

```
txtline6 = ts.ReadLine
stepsize = ts.ReadLine
txtline7 = ts.ReadLine
ncalpoints = ts.ReadLine
txtline8 = ts.ReadLine

For i = 1 To ncalpoints
    depthofcalculation(i) = ts.ReadLine
    Combo2.AddItem depthofcalculation(i)
Next i
iflag1 = True
End Sub

Private Sub mnuSave_Click()
If iflag2 = False Then
txtmessage = "Calculation must be performed before saving the results"
Else
txtmessage = "System Messages"
' Show the Save Dialog Box
CommonDialog1.ShowSave

' Open the File and write the results

txtReturn2 = CommonDialog1.Filename
Dim fso2 As New FileSystemObject, ts2 As TextStream
Set ts2 = fso2.CreateTextFile(CommonDialog1.Filename, ForWriting)

ts2.WriteLine (txtline1)
ts2.WriteLine (waveperiod)
ts2.WriteLine (txtline2)
ts2.WriteLine (waterdepth)
ts2.WriteLine (txtline2a)
ts2.WriteLine (waveheight)
ts2.WriteLine (txtline3)
ts2.WriteLine (deltat)
ts2.WriteLine (txtline4)
ts2.WriteLine (ndatapoints)
ts2.WriteLine (txtline5)

For i = 1 To ndatapoints
  ts2.WriteLine (measwaterpress(i))
Next i

ts2.WriteLine (txtline6)
ts2.WriteLine (stepsize)
ts2.WriteLine (txtline7)
ts2.WriteLine (ncalpoints)
ts2.WriteLine (txtline8)

For i = 1 To ncalpoints
  ts2.WriteLine (depthofcalculation(i))
Next i

ts2.WriteLine ("Calculated Total Stress (kPa)")
```

```
For i = 1 To ncalpoints
   ts2.WriteLine (calsigma(i))
Next i
End If
End Sub

Private Sub calwavelength(T, h, l)
g = 9.81
pi = 3.1415926
c1 = 2 * pi / T ^ 2

X1 = g / l
X2 = 2 * pi * h / l
X3 = X1 * (Exp(X2) - Exp(-X2)) / (Exp(X2) + Exp(-X2))

While c1 < X3
   l = l + 0.001
   X1 = g / l
   X2 = 2 * pi * h / l
   X3 = X1 * (Exp(X2) - Exp(-X2)) / (Exp(X2) + Exp(-X2))
Wend
wavelength = l
End Sub

Private Sub intpress(XL, XR, UL, UR, z, Step, sig)

pi = 3.1415926
sig = 0

UT = UR - UL
XT = XR - XL
du = UT / Step
dx = XT / Step
CU = UL + du / 2
CX = XL + dx / 2

For j = 1 To Step
   sig = 2 * z ^ 3 * dx * CU / (pi * (CX ^ 2 + z ^ 2) ^ 2) + sig
   CU = CU + du
   CX = CX + dx
Next j

End Sub
```

Sample Input File for Total Stress.exe

```
Wave Period (sec)
5.0
Water Depth (m)
1.25
Wave Height (m)
0.4
Time Between Data Points (sec)
0.1
Number of Data Points
11
Measured Water Pressure (kPa)
0.492510654
0.588867692
0.663336217
0.704258218
0.742087277
0.766354976
0.746607731
0.722340032
0.697358578
0.667856671
0.633834309
Integration Step Size
1000
Number of Calculation Points
21
Depths for Calculation (m)
0.001
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.18
0.20
0.22
0.24
```