Water Resources Center
Annual Technical Report
FY 2012

Introduction

During FY2012 the Rhode Island Water Resources Center has supported two research grants and one information transfer project. The two research projects explored two different areas of water supply and treatment. The first project "Water-Induced Pore Pressures in Remedial Caps in Reservoirs," was an investigation into the vulnerability of reservoirs which have had contaminated sediments covered with fill. Information from this project could be utilized to design reservoir remediation systems which would not fail due the action of surface waves. The second research project entitled "A Novel Fabrication Method for Antibacterial Membranes," was aimed at developing a porous membrane which was capable of disinfecting water without the addition of chemicals such as chlorine. The information transfer project supported a summer camp for middle and high school students and a clean water conference.

In addition to these activities, the Rhode Island Water Resources Center continued to partially support graduate and undergraduate students in research. Other activities included the website and newsletters.

Research Program Introduction

The Rhode Island Water Resources Center has supported two research proposals. The first proposal entitled "A Novel Fabrication Method for Antibacterial Membrane," was authored by Peng Wang. Shortly after his proposal was funded he passed away. Eugene Park, with the assistance of Stan Barnett was able to complete the research in his proposal. The basis for their research was to develop a safe method for disinfection of drinking water. Their hypothesis was that having antibacterial agents imbedded in membranes could be both effective and efficient. Development of a disinfection membrane technology could offer advantages over conventional chlorine disinfection in terms of not producing disinfection by-products (many of which can be cancer causing at high levels)and more efficient use of antibacterial materials.

The second funded project entitled, "Wave-Induced Pore Pressures in Remedial Caps in Reservoirs," was completed by PI Aaron Bradshaw. The objective of this project was to refine and validate a new strain-based model to predict the potential for wave-induced excess pore pressure generation in subaqueous sediment caps. His research is valuable in that one viable alternative for remediation of reservoirs containing contaminated sediments is to place a thick granular cap on the bottom sediments. His research involved developing a predictive method to determine the impact of reservoir surface waves on the stability of the sediment cap.

A novel fabrication method for antibacterial membrane

Basic Information

Title:	A novel fabrication method for antibacterial membrane
Project Number:	2012RI106B
Start Date:	3/1/2012
End Date:	2/28/2013
Funding Source:	104B
Congressional District:	Rhode Island
Research Category:	Water Quality
Focus Category:	Water Quality, Water Supply, None
Descriptors:	
Principal Investigators:	Eugene Park, Stanley Barnett

Publications

There are no publications.

A Novel Fabrication Method for Antibacterial Membrane

Eugene Park
Assistant Director of Technical Programs
New York State Institute of Pollution Prevention
Rochester Institute of Technology
and
Stanley Barnett
Emeritus Professor of Chemical Engineering
University of Rhode Island

Abstract:
The goal of this project is to test a composite membrane containing antimicrobial nanomaterials for drinking water purification at the household level. Three different fibrous mats with titanium dioxide(TiO_2) were prepared by an electrospinning process. The best results show two log reductions in bacterial counts with UV activated TiO_2.

Introduction:
Disinfection is an essential step for production of safe drinking water since its aim is to remove disease-producing microorganisms. The conventional way, using small micromole disinfectants, presents a paradox. On one hand, disinfection by-products (DBPs) of disinfectants can reduce the number of microorganism. On the other, however, these DBPs may also do harm to human beings. In order to obtain purified water as well as avoid the secondary pollution caused by DBPs, new disinfection materials and techniques are being developed. Having antibacterial agents imbedded in water-insoluble supports is both effective and efficient. It has three major advantages: DBPs can be avoided; antibacterial materials can be reused； sterilizing efficiency can be achieved because of high concentration of antibacterial agents on support surfaces. Developing new composite materials comprised of antibacterial agents and water-insoluble supports is attracting more and more attention. [1,2]

The goal of this project is to develop a composite material that can be used as a membrane with lasting antibacterial properties. An application of special interest for such a material is for drinking water purification at regular household during a power outage. The material has a multi-layer structure. Antibacterial agents will be imbedded in polymer fibrous mats. And commercially available membranes will be laminated together with the mats to form the product.

Electrospun nanofibers advantages:

Electrospinning is a process for making continuous nanofibers in a non-woven form. This process spins fibers ranging from 80 nm diameter to several hundred nanometers. Nanofibers have a small pore size and a large surface area to volume ratio compared to nonwovens. This ratio for a nanofiber can be as large as 103 times of that of a microfiber. This, together with the low density and interconnected open pore structure, makes the nanofiber nonwoven mat appropriate for a wide variety of filtration applications. An interesting feature of these microfiltration membranes (with a pore size of 0.1 to 0.4 µm) is the high clean water permeability (CWP) (N6000 l/m^2h bar) compared to other microfiltration membranes. This allows high flux operation of the membranes.

Procedure:

The agent-imbedded fibrous mats were prepared using an electrospinning [3] process by Nate Hansen, PhD, currently being commercialized by Cornell University. Three different mats with imbedded TiO_2 nanoparticles [4,5,6,7,8,9] were tested, as listed in Table 1. A control was added. Tests utilized *E.coli* K12 cultivated in LB medium at 37^oC for 18 hr [1,4,6]. Active bacteria werecounted and the antibacterial effect was calculated using following equation:

Antibacterial ratio=100%*(Number of original cells- Number of viable cells)/ Number of original cells) [1].

Twelve centrifuge tubes were prepared with 900 µl sterile water. 100 µl of filtrate was pipetted into centrifuge tube 1. Serial dilutions were then made using centrifuge tubes 2 to 12. Ten microliters were then pipetted onto LB agar plates and incubated at 37^oC for 13 hours. Three parallel experiments were run for each concentration. The number of colonies formed was recorded and an average of the three experiments calculated.

Materials:

Three samples were received and tested:
PVA-TiO_2
PAN-TiO_2
Ps-TiO_2

The microorganism that was tested was E.coli K12 cultivated at 37° C for 18 h.

First test: comparison of different samples

Samples:
0: no membrane with two filter papers
1: membrane PVA-TiO_2 with two filter papers
2: membrane PAN-TiO_2 with two filter papers
3: membrane PS-TiO_2 with two filter papers

Table 1 Experimental conditions:

Sample	Osmotic Pressure (bar)	Filtration Time (min)	Filtration Volume (ml)	Filtration Velocity (ml/min)
0	0.75	1	323	323
1	0.73	7	71.5	10.2
2	0.76	5	210	42
3	0.76	2	63	31.5

Table 2 Experimental results:

Sample	Average Bacterial Concentration (10^6 cfu/ml)	Standard Deviation	Antibacterial Ratio (%)
0	10.7	5.35	-77.8
1	7.7	2.16	-27.8
2	6.3	1.41	-5.6
3	7	1.63	-16.7
Unfiltered	6	2.45	

Analysis of results:

The orders of magnitude of the bacterial colonies with and without filtration are almost the same, which is quite different from the prediction that the bacterial concentration will drop 2 orders of magnitude. This is due to the fact that ultraviolet light is necessary to activate the TiO_2 for the antibacterial process. The reason why the number of bacterial colonies increased after filtration is believed to be self-contamination from the mats.

Second test: antibacterial examination of membrane PVA-TiO_2

Samples: membrane PVA-TiO_2 with two filter papers, UV=365 nm
0: original bacterium
1: filtrated without UV irradiation or pretreatment
2: filtrated with UV pretreatment for 20 min
3: UV irradiated for 20 min without filtration
4: filtrated with UV irradiation for 3min
5: UV irradiated for 3 min (control experiment for Sample 4)
6: filtrated with fluorescent pretreatment for 20 min

Table 3 Experimental conditions:

Sample	Filtration Pressure (bar)	Filtration Time (min)	Filtration Volume (ml)	Filtration Velocity (ml/min)
0	-	-	-	-
1	0.74	2	69	34.5
2	0.3	3	79	26.3
3	-	-	-	-
4	-	3	48	16
5	-	-	-	-
6	-	-	-	-

Some data failed to be recorded due to limited experimental conditions.

Table 4 Experimental results:

Sample	Average Bacterial Concentration (10^6 cfu/ml)	Standard Deviation	Antibacterial Ratio (%)
0	12.3	6.98	0
1	3	0	75.6
2	8.3	5.72	32.5
3	11.3	0.82	8.1
4	0.3	0.82	97.6
5	10.7	2.16	13.0
6	8.7	2.16	29.3

Analysis of results:

According to the standard reduction of bacteria criterion, less than 0–20% reductions indicates no bactericidal effect; between 20–50% reduction indicates a low bactericidal effect; between 50–70% reduction indicates an expressive bactericide; greater than 70% reductions is considered a powerful bactericidal effect.[5]

The highest removal ratio is in sample 4 pre-treated with UV irradiation for 3 min. The ratio of 97.6% is among the powerful bactericidal effect. Samples 2 and 6 showed that both fluorescent and UV pretreatment will increase the removal of bacteria. Samples 3 and 5 showed that UV inactivation without filtration in these systems are not remarkable during the experimental time scale. Sample 1 showed that filtration without UV irradiation or pretreatment can remove 75.6% bacteria, which is quite different from the former experiment in which no removal occurred. This may be indicative of the scale of error involved in the experiments.

Comparison of result with literature work:

There are no reports of disinfection by applying TiO_2 imbedded mats for filtration. However, the best reported antibacterial ratio for E. coli is 100% in 25-30 min by using immobilized TiO_2 nanotube electrodes. [8] The best result for disinfection using both filtration and nanoparticles imbedded in electrospun nanofibers is about 5.6 log_{10} CFU/100 ml removal [4], while the highest result in this study is 9.7 log_{10} CFU/100 ml removals. This is encouraging for future work.

Summary:

It was demonstrated that doping TiO_2 with silver greatly improved photo catalytic bacterial inactivation by UV-A activated TiO_2. An investigation of polymer-TiO_2-Ag samples may prove advantageous.

References:

[1] Preparation and antibacterial character of a water- insoluble antibacterial material of grafting polyvinylpyridinium on silica gel, Baojiao Gao , Sanxiong He, Jianfeng Guo, Ruixin Wang, Materials Letters (2007), 61(3), 877-883.

[2] Antimicrobial nanomaterials for water disinfection and microbial control: Potential applications and implications, Qilin Li, Shaily Mahendra, Delina Y. Lyon, Lena Brunet, Michael V. Liga, Dong Li,Pedro J.J. Alvarez, Water Research (2008), 42(18), 4591-4602.

[3] Functionality of nano titanium dioxide on textiles with future aspects: Focus on wool, Montazer Majid and Esfandiar Pakdel, J of Photochemistry and Photobiology, C: Photochemistry Reviews (2011), 12(4), 293-303.

[4] Potential of a functionalised nanofibre microfiltration membrane as an antibacterial water filter, N. Daels , S. De Vrieze , I. Sampers , B. Decostere , P. Westbroek , A. Dumoulin , P. Dejans ,K. De Clerck , S.W.H. Van Hulle .Desalination (2011), 275 (1-3), 285-290.

[5] Correlation between surface morphology and hydrophilic/hydrophobic conversion ofMOCVD-TiO2 films, H.Y. Lee, Y.H. Park, K.H. Ko, Langmuir 16 (2000) 7289–7293.

[6] Photocatalytic antibacterial performance of Sn4+-doped TiO2 thin films on glass substrate. Funda Sayılkan, Meltem Asiltürk, Nadir Kiraz, Esin Burunkaya, Ertu˘grul Arpac, Hikmet Sayılkan, J of Hazardous Materials (2009)162(2-3), 1309-1316.

[7] Effect of TiO_2 nanoparticles on the antibacterial and physical properties of polyethylene-based film. Yage Xing, Xihong Li, Li Zhang, Qinglian Xua, Zhenming Che,, Weili Li, Yumin Baia, Ke Li. Progress in Organic Coatings 73 (2012) 219– 224.

[8] Enhanced inactivation of E. coli bacteria using immobilized porous TiO_2 photoelectrocatalysis. Nir Baram, David Starosvetsky, Jeana Starosvetsky, Marina Epshtein,Robert Armon, Yair Ein-Eli. Electrochimica Acta 54 (2009) 3381–3386.

[9] Synthesis of antibacterial film CTS/PVP/TiO2/Ag for drinking water system. Liang Zhang, Xue Bai, Hua Tian, Lvling Zhong, Cailian Ma, Yuanzhen Zhou, Shuangli Chen, Dongliang Li. Carbohydrate Polymers 89 (2012) 1060– 1066.

Wave-Induced Pore Pressures in Remedial Caps in Reservoirs

Basic Information

Title:	Wave-Induced Pore Pressures in Remedial Caps in Reservoirs
Project Number:	2012RI110B
Start Date:	3/1/2012
End Date:	2/28/2013
Funding Source:	104B
Congressional District:	2
Research Category:	Engineering
Focus Category:	Water Supply, Sediments, Models
Descriptors:	
Principal Investigators:	Aaron Stephen Bradshaw

Publication

1. Julian, A. (2013). A Strain-Based Model to Screen for Wave-Induced Pore Pressure Generation in the Seabed. M.S. Thesis, Department of Ocean Engineering, University of Rhode Island, Kingston, RI.

WAVE-INDUCED PORE PRESSURES IN REMEDIAL CAPS IN RESERVOIRS

Aaron Bradshaw, Ph.D., P.E
Anthony Julian

DRAFT FINAL REPORT

Submitted to:
Rhode Island Water Resources Center
Project No. 000S3270

May 30, 2013

Abstract: This report summarizes the work completed for the project titled Wave-Induced Pore Pressures in Remedial Caps for Reservoirs funded by the Rhode Island Water Resources Center (Project No. 000S154). There is field evidence that remedial sediment caps may be adversely affected by the generation of excess pore water pressures from water waves. The objective of this project, therefore, was to refine and validate a strain-based model to predict the potential for wave-induced excess pore pressure generation in subaqueous sediment caps. First, the model is described in detail. Finite element analyses were performed to investigate the shear stress profiles in an inhomogeneous elastic sediment bed and develop normalized charts for design. Existing wave tank experiments performed on silt were used to validate the model. The difference between the shear stress profiles in the two-layered system and the homogeneous case was significant in some cases. A comparison of the factor of safety predicted using the strain-based method showed very good agreement to the excess pore water pressures measured in the wave tank experiments thus validating the approach. An example was also provided to demonstrate the practical implementation of the method.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

1.1 Background

Continued population growth combined with diminishing clean water sources reinforces the need to protect and/or enhance our existing reservoirs. There are some reservoirs in the New England region that contain bottom sediments that are contaminated with toxic chemicals. Examples include a reservoir in Wenham, MA having a historic deposit of fly ash containing arsenic (Kelly 2004) and the Neponset Reservoir containing metals in the bottom sediments (Mortimer 2010). In some cases dredging of contaminated sediments may not be economically feasible or may re-suspend sediment into the water column causing additional problems. Therefore, one option is to place a thick granular cap that over the contaminated sediment to serve as a barrier between the contaminated sediments and the water column.

The cap protects the water column in two ways: by physically holding contaminated sediment particles in place so that they cannot be transported into the water column from erosive forces (e.g., boat propellers), and provides some chemical filtering of pore fluid that may flow through the cap and into the water column. Therefore, the cap must remain in place under any environmental conditions to be effective.

If there is sufficient fetch, strong winds from storms can generate water waves that could adversely affect cap performance by generating excess pore water pressures in the cap or substrate sediments. The pore pressure generation is the result of two mechanisms as described in deGroot et al. (2006). In transient or momentary liquefaction the wave induces flow that temporarily reduces the effective stresses to zero in the near-surface sediments. The second type is residual liquefaction where the wave induces cyclic shear stresses in the bottom sediments that causes an accumulation of excess pore water pressures. This study focuses on the latter mechanism.

There is unpublished evidence at remedial sites in very shallow water where core samples have shown that the capping materials penetrated and mixed with the underlying sediments thereby reducing the effective cap thickness (Paul LaRosa, Anchor QEA, personal communication 2011). The cap failures were believed to be the result of wave action that induced excess pore pressures in the sediments leading to strength reduction and instabilities. Excess pore water pressures in the contaminated substrate sediments would also induce flow that could transport contaminants from the sediments into the water column.

Methods have been developed to predict the potential for water wave-induced residual liquefaction. However, these methods are highly uncertain when applied to sediment caps that are frequently are underlain by fine-grained sediments. The Author has developed a simple predictive model to evaluate the potential for the development of excess pore pressures from water waves in sediment caps. However, this model has not been validated which is the focus of this study.

1.2 Objectives

The objective of this study was to refine and validate a strain-based model that can be used to assess the pore pressure potential in remedial caps from water waves.

1.3 Scope of Work

The original scope of work focused on conducting wave tank experiments to validate the pore pressure model. However, wave tank data were identified in the literature that was suitable for this purpose. The research efforts, therefore, were directed at improving the accuracy of the model using finite element analyses and validating the model using existing wave tank data. The following scope of work was performed as part of this project:

- Perform a literature review on water wave-induced residual liquefaction,
- Document the strain-based method,
- Perform finite element analyses to investigate the accuracy of the method,
- Validate the method using existing wave tank data,

- Provide a worked example to demonstrate the implementation of the method.

1.4 Structure of the Report

This report is structured into five remaining sections. Section 2 provides an extensive literature review for both analytical methods and experimental studies pertaining to water wave induced residual liquefaction. Section 3 provides a description of the strain-based model and the input parameters. Section 4 discusses finite element analyses that were performed to investigate the influence of sediment inhomogeneity on the cyclic shear stresses applied by a passing wave. Section 5 validates the model by comparing model predictions to the results of wave tank experiments. Section 6 provides an example analysis followed by Section 7 that provides a summary and conclusions.

2.0 LITERATURE REVIEW

The literature review focuses on methods that have been used to analyze the accumulation of excess pore water pressures (i.e. residual liquefaction) in the sediment bed from water waves.

2.1 Analytical Methods

Seed and Rahman (1978) were the first to develop a method to predict ocean wave-induced liquefaction in the seabed. Their method encompasses both generation and dissipation mechanisms of pore pressure for clean sands. Pore pressure generation is based on laboratory derived equations that relate the pore pressure ratio, r_u , defined as the excess pore pressure divided by the initial effective vertical stress, to the cycle ratio, N/N_l, where N is the number of stress cycles during a storm and N_l is the number of cycles to cause liquefaction. Their method uses equations that are solved using a numerical analysis allowing the seabed to be discretized into layers representing different sediment characteristics and rates of pore pressure generation.

Finn et al. (1983) developed a computer program called STAB-W to compute residual pore pressures in the seabed and evaluate liquefaction potential. Their analysis is a generalization of Seed and Rahman's approach; however, considers the changes to moduli and shear stress levels as excess pore pressure accumulates.

Although the above procedures may be warranted for projects in which liquefaction could result in costly and unfavorable consequences, simplified approaches have been proposed for sands to reduce time and expense by conservatively assuming undrained conditions (e.g. Nataraja and Gill 1983; Ishihara and Yamazaki 1984). Nataraja and Gill's method is based on correlations developed for seismic liquefaction that relate cyclic strength to Standard Penetration Test (SPT) blow counts. The correlations were adjusted for ocean wave loading to account for more severe degradation effects and higher numbers of cycles. An analysis is performed by estimating the cyclic strength from SPT blow counts and comparing them to the cyclic shear stresses induced in the seabed for an equivalent number of ocean wave cycles.

Ishihara and Yamazaki (1984) developed a stress-based method based on undrained cyclic triaxial torsion shear tests on loose sands to determine the cyclic strength. The tests were able to mimic the stress path in the field where there is continuous rotation of principle stresses. This experimental data was used in part to derive charts that can be used to assess liquefaction potential at a site under a specified wave condition. The cyclic stresses in the sediments were estimated using elastic solutions for a homogeneous elastic halfspace.

2.2 Experimental Studies

There have been a few studies of residual liquefaction that have been based on cyclic strength tests on undisturbed sediment samples (e.g., Lee and Focht 1975, Clukey et al. 1985) and on small-scale wave tank experiments (e.g., Clukey et al. 1980).

2.3 Synthesis

Based on a review of the literature the available analytical methods for predicting pore pressure accumulation from water waves are stress-based and were derived from data on clean sands. Use of these methods, therefore, is highly uncertain in fine-grained sediments or in sands containing fines. At silt sites laboratory tests have been used to characterize the cyclic strength of soils. However, this is also uncertain considering the difficulty in obtaining undisturbed samples of cohesionless soils using conventional sampling methods. Moreover, research has shown that cyclic resistance of reconstituted samples is highly affected by the method of sample preparation.

The stress–based methods also require the determination of an equivalent number of loading cycles to cause liquefaction. Although this approximation has been well established for seismic liquefaction, the determination of an equivalent number of cycles for a storm wave loading is not well established. A simple strain-based method is described next that avoids some of the issues described above.

3.0 DESCRIPTION OF THE PROPOSED METHOD

A simple strain-based method to screen for wave-induced pore pressure generation in the seabed is modified after Bradshaw (2012) and is shown to be applicable for a wide range of seabed characteristics. It is well known that water waves apply a sinusoidal shaped pressure on the bottom that causes cyclic shear stresses and normal stresses in the sediment bed as shown in Figure 1. The magnitude of the cyclic stresses is related to the wave height (H), still water depth (d), wavelength of the ocean wave (λ), and the depth below the sediment bed (z). The proposed method uses a total stress analysis whereby the shear strains induced by a passing wave are compared to the shear strains needed to generate excess pore water pressures (i.e. the threshold shear strain).

The threshold shear strain concept was initially conceived by Dobry et al. (1982) to evaluate seismic soil liquefaction potential. The basis for the method is shown in Figure 2 which plots pore pressure ratio, defined as the excess pore water pressure divided by the initial effective confining pressure, versus cyclic shear strain amplitude for various undrained cyclic triaxial test results. These results include 8 different sands, 4 different sample preparation methods, and a wide range of confining pressures. Figure 2 indicates that when the induced shear strains remain below the threshold shear strain no residual pore water pressures develop. One of the key features of Figure 2 is that the threshold shear strain is independent of confining stress, density, and fabric (i.e. sample preparation method).

The potential to generate residual pore pressures can therefore be expressed as a factor of safety:

$$FS = \frac{\gamma_t}{\gamma} \qquad (1)$$

where FS=factor of safety, γ_t=threshold shear strain of the sediment, and γ=cyclic shear strain induced in the sediment. A factor of safety of less than one indicates that the induced cyclic shear strain is higher than the threshold shear strain and thus has the potential for residual pore pressure generation. Note, however, that a factor of safety of less than one does not provide an indication of the magnitude of pore water pressures or if initial liquefaction will occur. Higher factors of safety should be used to account for the uncertainties in the model and input parameters such that an acceptable level of reliability is achieved. Acceptable factors of safety can be established through analysis of case histories and/or probabilistic methods that are beyond the scope of this study.

There are two potential issues in applying the threshold shear strain concept developed for seismic loading to the problem of water wave loading. First, threshold shear strain values for saturated soils are typically developed from undrained laboratory cyclic tests. An undrained condition is a reasonable assumption in cohesive sediments during water wave loading. However, partial drainage can occur in cohesionless sediments during wave loading (Seed and Rahman 1978), but the assumption of undrained conditions is conservative. Second, existing threshold shear strain values were determined from tests having roughly 10 to 30 loading cycles that is consistent with earthquake loading. Storms will induce many orders of magnitude more cycles. Studies suggest, however, that the number of loading cycles has negligible effect on the threshold shear strain (Erten and Mayer 1995; Hsu and Vucetic 2006; Hazirbaba and Rathje 2009).

3.1 Estimation of Cyclic Shear Strain

The cyclic shear strains are the result of the cyclic pressures that are applied to the bottom from a passing water wave. The amplitude of bottom pressure (p_0) from linear wave theory is given by the following (Finn et al. 1983):

$$p_0 = \frac{\gamma_w H}{2\cosh(k\,d)} \tag{2}$$

where γ_w=unit weight of water, k=wave number (=2π/λ where λ is the wavelength of the passing water waves), d=water depth, H=wave height (peak to trough) as shown in Figure 1. The amplitude of the horizontal and vertical cyclic stresses induced at any specified depth in an elastic half space is proportional to the applied bottom pressure and thus can be described by a shear stress influence factor as follows:

$$\tau_h = p_0 I \quad (3)$$

where τ_h=shear stress on the horizontal (and vertical) plane, and I= shear stress influence factor. Solutions for the horizontal stresses under a sinusoidal bottom pressure have been developed for a homogeneous elastic half-space (Fung 1965). The solution expressed as an influence factor is as follows:

$$I = kz \exp(-kz) \quad (4)$$

where k = wave number as defined previously. Equation 4 is also plotted in Figure 3. The figure shows that the maximum shear stress occurs at a depth of approximately 0.2 times the wavelength and the shear stresses become negligible at a depth of approximately 1 wavelength.

In marine deposits the sediment is not homogeneous, and can be highly stratified or may have stiffness properties that change with depth. Applying Equation 4 in these deposits is uncertain. To address this issue, finite element analyses were performed to determine shear stress influence factors for an inhomogenous elastic bed. These analyses are described in detail in Section 4 of this report.

The shear strain induced in the sediment bed from an applied shear stress can be estimated from the shear modulus of the sediment:

$$\gamma = \tau_h / G \quad (5)$$

where τ_h = the cyclic shear stress induced by the passing wave and G = the secant shear modulus.

The stress-strain behavior of a soil under cyclic loading is nonlinear even below the threshold shear strain level and thus an equivalent linear analysis is used to estimate shear strains. The secant shear modulus is defined as:

$$G = G_o \left[\frac{G}{G_0}\right]_\gamma \tag{6}$$

where G_0= small strain shear modulus, $[G/G_o]_\gamma$ = the modulus degradation factor which is dependent upon the cyclic shear strain amplitude as denoted by the subscript γ. By substituting Equation 3 and 6 into Equation 5, the shear strain induced in the sediment can be written in the following general form:

$$\gamma = \frac{p_0 I}{G_o \left[G/G_o\right]_\gamma} \tag{7}$$

To calculate the shear modulus from Equation 7, the measurement of the small shear strain modulus is required. The most direct method for obtaining G_0 is through measurement of the shear wave velocity using the following relationship:

$$G_o = \rho V_s^{\,2} \tag{8}$$

where V_s = shear wave velocity, ρ = total density of the soil. Numerous methods have been proposed to measure the shear wave velocity in situ including methods using cross-hole, down-hole, and inversion techniques such as Multichannel Analysis of Surface Waves (MASW). An underwater MASW system has recently be developed and tested at the University of Rhode Island, for example (Giard 2013).

If in-situ measurements of the shear wave velocity cannot be obtained or if the properties of a sediment cap have to be estimated before it is placed the following empirical relationship may be considered for normally consolidated soils (Hardin and Black, 1968; Hardin, 1978):

$$G_o = \frac{625}{0.3 + 0.7e^2}\sqrt{p_a \sigma_m'} \qquad (9)$$

where e = void ratio, σ_m' = mean effective confining pressure, and p_a = reference pressure in the same units as G_o and σ_m'. The mean effective confining pressure can be given as $\sigma_v'(1+2K_o)/3$; where σ_v' = the vertical effective stress and K_o = lateral earth pressure coefficient. Equation 9 was derived from resonant column tests for clays and sands and represents an average trend.

Numerous modulus degradation curves have been proposed in the literature for the purpose of modeling site response in earthquake engineering. The authors prefer the degradation curves from Ishibashi and Zhang (1993) because they are based on an extensive soil database and consider the effects of both mean effective confining stress and soil plasticity. The equations are listed below:

$$\left[\frac{\mathrm{G}}{\mathrm{G_o}}\right] = \mathrm{K}(\sigma_\mathrm{m}')^\mathrm{m} \qquad (10a)$$

$$K = 0.5\left\{1 + \tanh\left[\ln\left\langle\left(\frac{0.000102 + n}{\gamma}\right)^{0.492}\right\rangle\right]\right\} \qquad (10b)$$

$$n = \begin{Bmatrix} 0 & for \quad I_p = 0 \\ 3.37\times10^{-6} I_p^{1.404} & for \quad 0 \le I_p \le 15 \\ 7.0\times10^{-7} I_p^{1.976} & for \quad 15 \le I_p \le 70 \\ 2.7\times10^{-5} I_p^{1.115} & for \quad I_p \ge 70 \end{Bmatrix} \qquad (10c)$$

$$m = 0.272\left\{1 - \tanh\left[\ln\left\langle\left(\frac{0.000556}{\gamma}\right)^{0.4}\right\rangle\right]\right\}\exp\left(-0.0145 I_p^{1.3}\right) \qquad (10d)$$

where I_p =plasticity index. Since the modulus degradation factor depends on the level of cyclic shear strain, the factor must be determined iteratively. This process will be described later.

Current degradation curves are based largely on resonant column tests that do not represent the stress path for water waves (i.e. continuous principle stress rotation). The stress path of water wave loading has been shown to be more damaging than for direct simple shear. For example, Ishihara and Yamasaki (1984) showed a 30% reduction in cyclic strength under continuous principle stress rotation as compared cyclic torsional shear conditions. However, it is uncertain how this translates to a reduction in shear modulus.

The degradation curves above also do not consider the effects of pore pressure generation. However, the approach presented herein uses a total stress analysis with no assumed pore pressure generation and thus the curves are applicable.

3.2 Estimation of the Threshold Shear Strain

The threshold shear strain has been measured in both cyclic triaxial and direct simple shear tests. For a site-specific analysis it may be desirable to perform these tests on representative sediment samples. Given that the threshold shear strain is insensitive to sample preparation, it can be obtained using reconstituted samples in the laboratory. However, in lieu of laboratory data it is possible to select threshold shear strain values from the literature. Hsu and Vucetic (2006) compiled threshold shear strain values for a range of soil types. The data, shown in Figure 4, suggest that threshold shear strain is well correlation to plasticity index. Therefore, this figure can be used to estimate the threshold shear strain for a particular soil if the Atterberg limits are obtained.

3.3 Analysis Procedure

The first step in the process is to determine the wave climate at the site of interest. Oceanographic data is typically only available from deep water locations. Therefore, if the site is located near-shore, a probabilistic design deep water wave height and wave period must be calculated and propagated to the site. This process is beyond the scope of this report and often requires detailed analyses that encompass phenomena such as shoaling, refraction, and diffraction for site-specific bathymetric terrain. Once the oceanographic parameters are obtained (wavelength, wave number, wave height, still water depth) the following description is meant to serve as a general guideline to implement the model.

The model is based on the comparison of the threshold shear strain to the induced cyclic shear strain in the seabed to determine a factor of safety against pore pressure generation at a specified depth below the seafloor (Equation 1). To determine these factors, a site investigation is required to obtain information on soil types and stratigraphy, plasticity index, and small strain shear modulus. Based on the shear stress profile shown in Figure 3, the soil conditions need only be evaluated to a depth of one wavelength below the mudline.

The threshold shear strain is selected at the specified depth from Figure 4 based on the measured plasticity index of the soil.

The induced shear strain is calculated at the specified depth using Equation 7. This requires the estimation of the cyclic shear stress that is based on the anticipated modulus profile at the site of interest. Therefore, it is recommended that a G_0 profile be developed first which is then used to guide the selection of the appropriate influence factor. For example, if the shear modulus profile is approximately constant with depth than Equation 4 may be applicable. Other shear modulus profiles are explored in the next section. The calculation of induced shear strain also depends on the modulus degradation that is a function of shear strain. Therefore, an iterative procedure must be used as follows:

1) Assume a value of [G/G_o].
2) Calculate a shear strain from Equation 7 using [G/G_o] from step 1.

3) Calculate $[G/G_o]$ from Equation 10 using the strain calculated in Equation 2.
4) Compare the assumed and calculated values of $[G/G_o]$.
5) Adjust the assumed value of $[G/G_o]$ and repeat the steps until the assumed and calculated values match.

The above process can be repeated for various depths to construct profiles of threshold shear strain and induced shear strain. These results are then used to calculate a factor of safety profile with factors of safety of less than one indicating the potential for excess pore pressure generation.

4.0 FINITE ELEMENT ANALYSIS

A finite element (FE) analysis was performed to investigate the shear stress profiles in an inhomogeneous elastic halfspace that might more closely represent the soil conditions encountered in the field. This was accomplished by performing a linear elastic analysis to develop normalized cyclic shear stress charts for a two-layered profile and a profile having a linearly increasing shear modulus with depth. The numerical simulations were performed using a commercial finite element program under plane strain conditions. The development of the FE model and the modeling results are described below.

4.1 Development of Finite Element Models

The FE models had a width and a depth equal to twice the wavelength (λ) in order to minimize boundary effects. This was based in part from trial and error as well as using Figure 3 as a basis to conclude that values of the shear stress at depths greater than one wavelength into the sediment bed are negligible. To best represent conditions seen in the field, boundary conditions of the models were unrestrained at the sediment surface, fixed in the horizontal direction on both side boundaries and fixed in both the horizontal and vertical directions along the bottom boundary.

The meshes of both models consisted of 200 external nodes and elements of 4 nodal quadrilateral shape. The software program contained a built-in mesh generation function allowing for the most accurate and optimized mesh quality. Built-in mesh quality functions were also used for the software program to reinforce an accurate mesh. An external load representing that of water wave loading (i.e. a sinusoidally shaped bottom pressure), was constructed on the free surface by using a triangular distribution that was discretized on the sediment surface into $\lambda/32$ segments.

Before constructing the layered models, a homogeneous elastic model was constructed and the results were compared to the analytical solutions to validate the model output. Two models were then constructed to represent shear modulus profiles for a two-layered system and a linear increasing shear modulus with depth as shown in Figure 5. The numerical analyses were performed at different spatial scales to ensure that the shear stress plots could be normalized.

4.2 Numerical Results

Two-Layered Shear Modulus Profile

The two-layered elastic model was described by two parameters: the thickness of the top layer, T, and the ratio of the shear modulus of the top layer to the shear modulus of the bottom layer. The top layer thickness (T) was modeled by constructing the interface between the two layers at normalized depths of $\lambda/16$, $\lambda/8$, $\lambda/4$, $\lambda/2$, and $3\lambda/4$. Each of the layers was assigned homogenous shear modulus values corresponding to shear modulus ratios of 0.1, 1.0, and 10 to provide a range of possible values.

Figures 6 through 10 summarize the finite element results in the form of dimensionless charts. These figures all show similar trends; however, are dependent on the location of the layer interface relative to the depth of the maximum shear stress in the homogeneous case (i.e. G1/G2 =1.0). As the depth of the interface gets closer to the depth of maximum shear stress in the homogeneous case, the effect on the calculated shear stress becomes more pronounced. This is illustrated in Figure 7, for example, where the interface was close to the depth of the maximum shear stress in the homogeneous case. The maximum normalized shear stress was 0.76 in the upper layer as compared to 0.36 in the homogeneous case.

As expected as the thickness of the top layer gets very thin (i.e. $T \rightarrow 0$) or very thick (i.e. $T \rightarrow \infty$) than the finite element results approach the homogenous solution.

The results also suggest that that if the cap is composed of a stiffer soil than the substrate sediment, for example a dense sand cap, it can “protect” the substrate by reducing the cyclic shear stresses in this layer.

Linear Increasing Shear Modulus Profile

To model a linearly increasing modulus profile with depth, the numerical domain was discretized into many thin layers (Figure 5b) and a constant shear modulus was applied in each layer. The analysis used two parameters: G_i and G_λ —which represent the shear modulus located at the mudline and one wavelength respectively. Different ratios of G_i /G_λ (designated as α) are plotted in Figure 11.

As expected, as α approaches a value of 1, the shear stress profile approaches the homogenous solution. The shear stresses in the linearly increasing profile were lower than the homogeneous case at normalized depths of less than 0.3, and higher below this depth. The differences between the homogeneous case and the case of a linearly increasing modulus profile are relatively small. For example, for an alpha of 1.0 the shear stresses are roughly 20% less than in the homogeneous case.

5.0 EXPERIMENTAL VALIDATION OF THE STRAIN-BASED METHOD

The strain-based method was validated by comparing results obtained from published wave tank experiments on silt (Clukey et al. 1983). A general description of the wave tank experiment, modeling details, and a comparison of the results is discussed below. For further details on wave tank experiments refer to Clukey et al. (1983).

5.1 Description of Wave Tank Experiments

Figure 12 presents the dimensions of the wave tank used in the experiment. The wave tank is 17.1 m-long, 0.76 m-wide, and 0.91 m-deep in the main section of the tank. The middle of the wave tank houses a 4.57 m-long and 0.84 m-deep sediment basin. Three test runs were selected from the experiment to compare to the model: Test 7-1, 7-2, and 7-3 (adopting the same notation of Clukey et al.). The three tests ranged in wave heights from 0.9 m to 0.23 m and contained a constant water depth of 0.53 m. Pore pressure transducers were embedded at various depths within the sediment basin to measure excess pore pressure and it was observed that minimal to intense liquefaction occurred for each of the sequential tests. Table 1 summarizes the wave conditions and measurements of pore pressure ratios, r_u, for each test - where the pore pressure ratio is defined as the excess pore pressure divided by the initial effective overburden stress.

The wave tank experiment was conducted on Danby silt which can be characterized as a late Pleistocene glacial outwash deposit that was deposited during the last ice epoch in a lacustrine environment (Clukey et al., 1983). The silt was prepared in the wave tank by pumping slurry through a hydraulic line after which the silt was allowed to settle in the sediment basin.

5.3 Modeling Details

The shear modulus used in the modeling was inferred from direct simple shear tests performed by Clukey et al. on Yukon silt and filter sand. The Yukon silt had similar grain characteristics to Danby silt. The simple shear tests were performed at initial vertical effective stresses of up to 10 kPa consistent with the overburden stress levels in the wave tank sediment basin. The results shown in Figure 14 show a linearly increasing shear modulus profile with depth.

The wavelength in the wave tank experiments was much greater than the depth of the silt basin and therefore the shear stress would likely be affected by the sediment basin boundaries. To address this issue a FE model of the wave tank was constructed to calculate the shear stress profile for each of the wave tank experiments. A linearly increasing shear modulus profile was assumed in the FE model (α=0) based on Figure 13. Given that the shear modulus interpreted from a direct simple shear test is not a small strain modulus, no modulus degradation was applied. The calculated shear stress profiles shown in Figure 14 were used in combination with Equation 5 to calculate the induced shear strains within the sediment for each test.

The threshold shear strain for the wave tank sediments was selected using the average value of 1.55E-4 for a non-plastic soil (Figure 4) to calculate a factor of safety against the generation of pore pressure.

5.4 Comparison of Modeled and Experimental Results

Figure 15 compares the factors of safety for the model and the measured pore pressure ratios for Test 7-1. Of the three tests, Test 7-1 had the lowest wave height and was the only test where residual pore pressures were not generated in one of the pore pressure transducers. As shown in Figure 15 the trends in measured pore pressure ratio and modeled factor of safety compare very well. For example, as the pore pressure ratio decreases to approximately zero at a depth of 0.66 m, the factor of safety trends above 1.0. A ±10% range in the shear modulus (dotted line) still compared well to the measured results.

Figures 16 and 17 compare the factors of safety for the model and measured pore pressure ratios for Tests 7-2 and 7-3 respectively. In these two tests, the pore pressure transducers all measured significant excess pore pressures in the sediment and Test 7-3 had higher values than Test 7-2. Figures 16 and 17 also reflect similar trends as in Figure

15 by predicting factors of safety less than one in the silt. In comparison of these two figures, Figure 17 shows relatively lower factors of safety than Figure 16 consistent with larger pore pressure ratios.

As discussed previously the modulus of the silt in the test basin was assumed to be comparable to the modulus measured on a different silt in the direct simple shear test. In addition, with the exception of Test 7-1, the shear modulus would increase after each successive test due to the previous wave exposure; however, since Test 7-1 was first, and produces more significant trends to the model validation, this effect is inconsequential. Despite these uncertainties the model results agree very well with the wave tank experiments thereby giving some validity to the proposed strain-based approach.

6.0 EXAMPLE ANALYSIS

The purpose of this section is to provide a worked example showing the practical implementation of the method.

Consider a hypothetical remedial site located in shallow water at the end of a 12 km-long reservoir. The soil conditions at the site consist of a thick contaminated organic silt deposit (PI=20; w_n=129%). It is proposed to place a 1 meter-thick sand cap on the silt that will result in an average still water depth of 2 meters. A fetch and depth limited wave analysis was performed for the reservoir using 50 mph winds to obtain a wave height of 0.79 meters, wave period of 3.49 seconds, and wavelength of 13.8 meters. These wave parameters were evaluated using equations 3-39 and 3-40 of the Shore Protection Manual (USACE 1984).

The sand cap will be placed by a spreader and thus is assumed to be deposited in a very loose condition having a void ratio of 0.8, a total unit weight of 18kN/m^3, and an effective friction angle of 30°. A friction angle of 30° was also assumed for the silt. It is assumed that the silt will fully consolidate under the weight of the cap to a final void ratio of 3.0. However, the analysis could also be performed to look at the conditions immediately after placement of the cap before the silt has time to consolidate.

The wave parameters above were used to calculate the amplitude of the bottom pressure (2.68kPa) from Equation 2. Next the small strain shear modulus profile was calculated at regular depth intervals using Equation 9 and plotted in Figure 18. To calculate the mean effective confining stresses at-rest conditions were assumed using the equation $K_0 = 1 - \sin\phi'$. As shown in Figure 18 the cap and silt soil profile can be represented as a two-layered system. Average G_0 values of 11 MPa and 4.5 MPa were calculated for the cap and silt layer respectively, which yielded a shear modulus ratio of 2.4.

Using the shear modulus ratio and Figure 6, the influence factor was determined by interpolating between values of 1.0 and 10. The cyclic strain was calculated with depth using Equation 7 and is plotted in Figure 19. The secant shear modulus is plotted in Figure 18 showing that some degradation occurred. Figure 4 was used to select threshold shear strain values of 1.55E-4 and 4.55E-4 for the cap and organic silt, respectively. The factor of safety against pore pressure generation was calculated using Equation 1 and is plotted in Figure 20. The model shows a factor of safety of less than 1.0 at depths between 1 to 2 meters suggesting the potential for residual pore pressure generation at this depth.

7.0 CONCLUSIONS

The objective of this study was to refine and validate a newly proposed strain-based model that can be used to assess the potential to generate excess pore water pressures in remedial caps. The method is based of the estimation of the induced shear strains from a passing wave and comparing them to the threshold shear strain. The threshold shear strain is well documented in the literature and the values are insensitive to soil type, confining pressure, and numbers of cycles. Excess pore water pressures are presumed to occur when the induced shear strain exceeds the threshold shear strain. Cyclic shear strains are estimated from the applied horizontal cyclic shear stress and the shear modulus of the sediments.

Finite element analyses were performed to develop normalized charts to estimate the cyclic shear stresses in a two-layered elastic half-space and a half-space that has a linear increasing modulus with depth. The method was validated by modeling a set of wave tank experiments that were performed in the 1980s on non-plastic silt. The factors of safety predicted by the model were in very good agreement with the measured excess pore pressure response. Finally, an example was provided to show how the method can be implemented in practice. The example represented the conditions that might occur in a large reservoir in shallow water. The model results showed the potential for excess pore pressured immediately beneath the sand cap for the hypothetical case.

8.0 REFERENCES

Bradshaw, A.S. (2012). "A Strain-Based Model to Screen for Residual Pore Pressures in Sediment Caps." *Proceedings of the ASCE 2012 Geo-Congress*, 4069-4078.

Clukey, E.C., Cacchione, D.A., and Nelson, C.H. (1980). "Liquefaction potential of the Yukon prodelta, Bering Sea." *Proccedings of the Offshore Technology Conference*, Houston, Texas.

Clukey, E.C., Kulhawy, F.H., and Liu, P.L.-F. (1983). "Laboratory and field investigation of wave-sediment interaction." Report on Grant CEE-8200272 to National Science Foundation Washington, D.C.

Clukey, E.C., Kulhawy, F.H., and Liu, P.L.-F. (1985). "Response of silts to wave loads: Experimental study," Strength testing of marine sediments, Laboratory and in-situ measurements, ASTM STP 883, R.C. Chaney and K.R. Demars, Eds., American Society for testing and materials, Philadelphia, 1985, pp. 381-396.

de Groot, M.B., Bolton, M.D., P. Foray, P., Meijers, P., Palmer, A.C., Sandven, R., Sawicki, A., and Teh, T.C. (2006). "Physics of liquefaction phenomena around marine stuctures." *Journal of Waterway, Port, Coastal, And Ocean Engineering*, ASCE, 132(4), 227-243.

Dobry, R., R. S. Ladd, F. Y. Yokel, R. M. Chung, and Powell, D. (1982). "Prediction of pore water pressure buildup and liquefaction of sands during earthquake by the cyclic strain method," *NBS Building Science Series 138*, National Bureau of Standards, Gaithersburg, Maryland: 150.

Erten, D. and Mayer, M.H. (1995). "Ccyclic undrained behavior of silty sand." *Soil Dynamics and Earthquake Engineering*, 14, 115-123.

Fung, Y.C. (1965). *Foundations of Solid Mechanics*, Prentice Hall, New Jersey, p.

195-197.

Finn, W.D.L., Siddharthan, R., and Martin, G.R. (1983). “Response of seafloor to ocean waves.” *Journal of Geotechnical Engineering*, ASCE, 109 (4), 556-572.

Giard, J.L. (2013). “An inversion scheme for the shear wave speed using scholte wave dispersion.” Masters. Thesis. University of Rhode Island: U.S.

Hardin, B.O. (1978). “The nature of stress-strain behavior of soils.” *Proceedings of the ASCE Geotechnical Engineering Division Specialty Conference on Earthquake Engineering and Soil Dynamics*, Vol. 1, 3-90.

Hardin, B.O. and Black, W.L. (1968). “Vibration modulus of normally consolidated clay.” *Journal of the Soil Mechanics and Foundation Division*, ASCE, 94(2), 353-369.

Hazirbaba, K. and Rathje, E.M. (2009). Pore pressure of silty sands due to induced cyclic chear strains, Journal of Geotechnical and Geoenvironmental Engineering, ASCE 135(12), 1892-1905.

Hsu, C.-C. and Vucetic, M. (2006). Threshold shear strain for cyclic pore-water pressure in cohesive soils. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 132(10), 1325-1335.

Ishibashi, I. and Zhang, X. (1993). “Unified dynamic shear moduli and damping ratios of sand and clay.” *Soils and Foundations*, 33(1), 182-191.

Ishihara, K. and Towhata, I. (1983). “Cyclic response to rotation of principal stress directions as induced by wave loads.” *Soils and Foundations*, 23(4), 11-26.

Ishihara, K. and Yamazaki, A. (1984). “Analysis of wave-induced liquefaction in seabed deposits of sand.” *Soils and Foundations*, 24(3),85-100.

Kelly, M. (2004). "Tighter rules for coal ash disposal." *Gulf of Maine Times*, Winter 2004.

Lee, K.L. and Focht, J.A. (1975). "Liquefaction potential at Ekofisk Tank in North Sea," Proc. ASCE, Vol. 101, GT1, pp. 1-18.

Mortimer, F. (2010). "Board backs cleanup of Neponset River." *The Foxboro Reporter*, September 30, 2010.

Nataraja, M.S. and Gill, H.S. (1983). "Ocean wave-induced liquefaction analysis." *Journal of Geotechnical Engineering*, 109(4), 573-590.

Rosenblad, B.L. (2000). "Experimental and theoretical studies in support of implementing the spectral-analysis-of-surface-waves (sasw) method offshore," Ph.D. dissertation, University of Texas at Austin, August 2000.

Seed, H.B. and Rahman, M.S. (1978). "Wave-induced pore pressure in relation to ocean floor stability of cohesionless soils." *Marine Geotechnology*, 3(2), 123-150.

Seed, H.B., Tokimatsu, K., Harder, L., and Chung, R. (1985). " Influence of SPT Procedures in Soil Liquefaction Resistance Evaluations." *J. Geotech. Engrg*., 111(12), 1425-1445.

Sumer, B. Mutlu, and Jørgen Fredsøe. *The Mechanics of Scour in the Marine Environment*. River Edge, NJ: World Scientific, 2002. 445-503. Print.

USACE (1984). *Shore Protection Manual.* Coastal Engineering Research Center U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg Mississippi.

Table 1. Wave parameters and results from the Clukey et al. experiment.

Test number	Wave period (s)	Wave height (m)	Wave length (m)	Depth (m)	Pore-water pressure ratio, r_u
7 -1	1.76	0.09 to 0.10	3.55	0.06	0.365
				0.23	0.277
				0.28	0.242
				0.62	0.069
7 - 2	1.79	0.15 to 0.16	3.63	0.06	0.832
				0.23	0.606
				0.28	0.773
7 - 3	2.02	0.20 to 0.23	4.20	0.06	1.46
				0.23	0.761
				0.28	0.70
				0.62	0.385

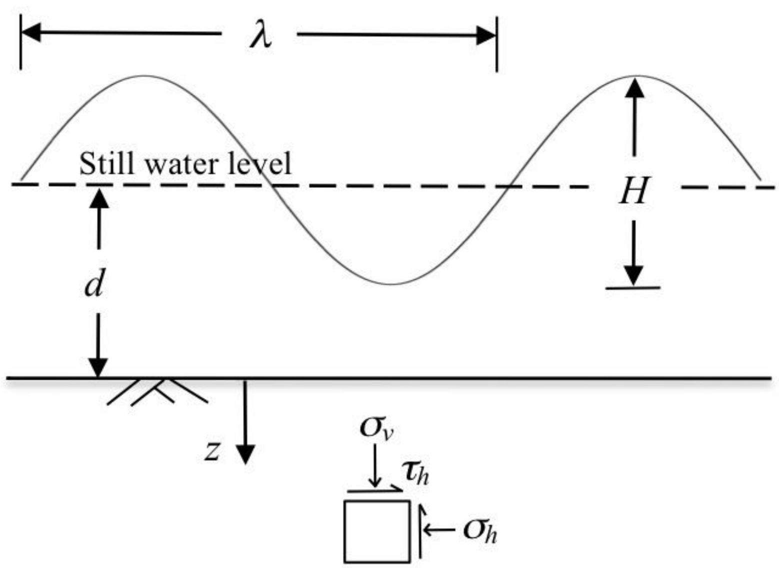


Figure 1. Schematic of water-wave induced stresses.

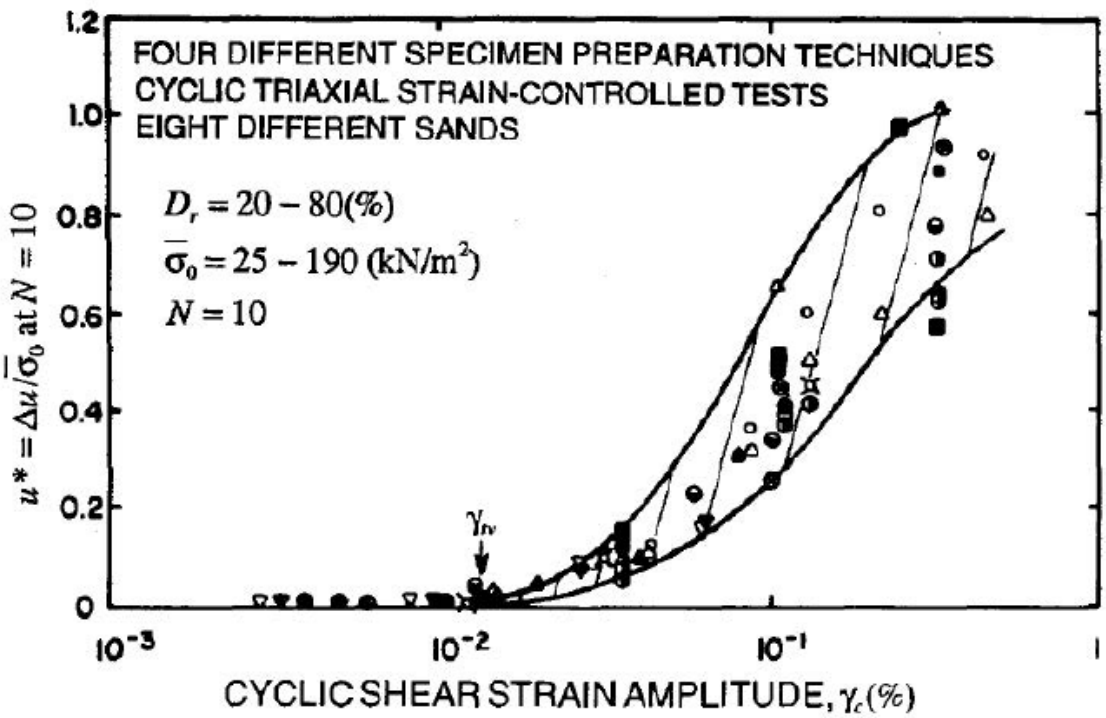


Figure 2. Pore pressure ratios generated in a variety of sands under cyclic loading (Vucetic, 1994 after Dobry et al. 1982).

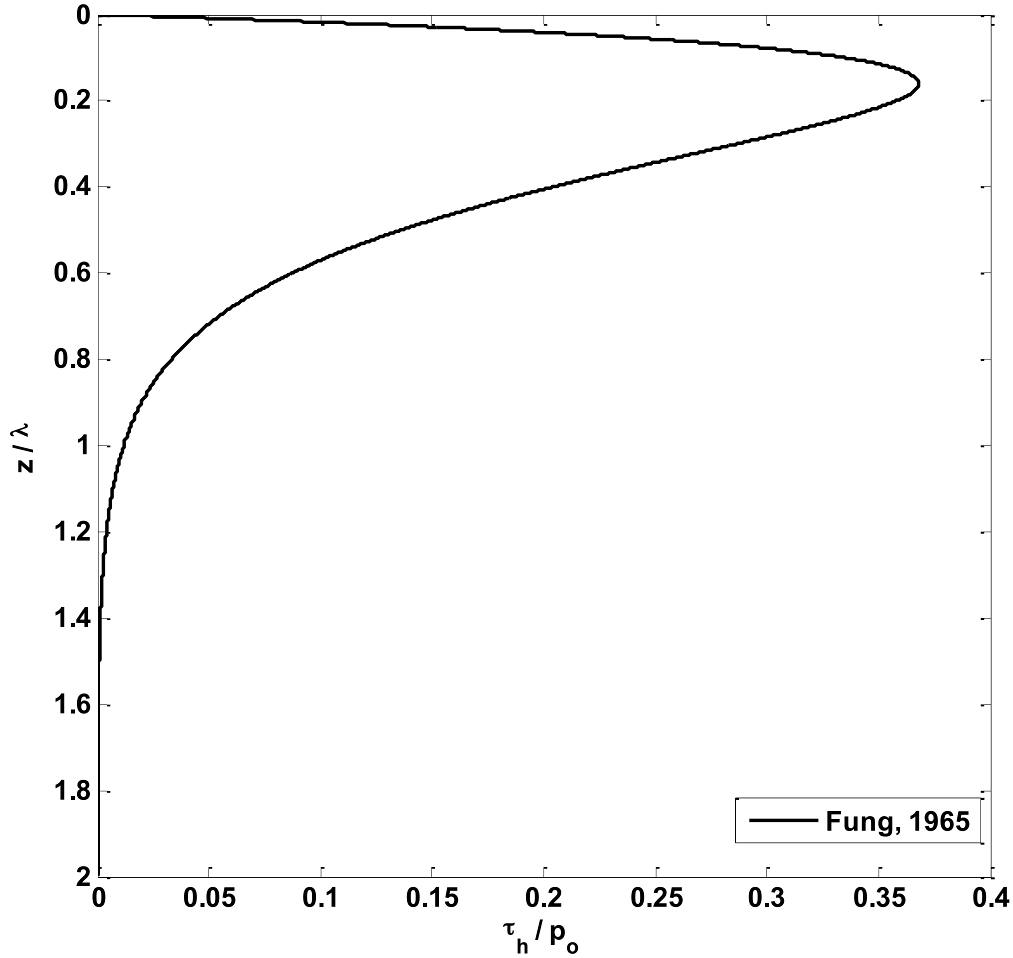


Figure 3. Normalized shear stress profile for wave loading on a homogeneous elastic halfspace as derived by Fung (1965).

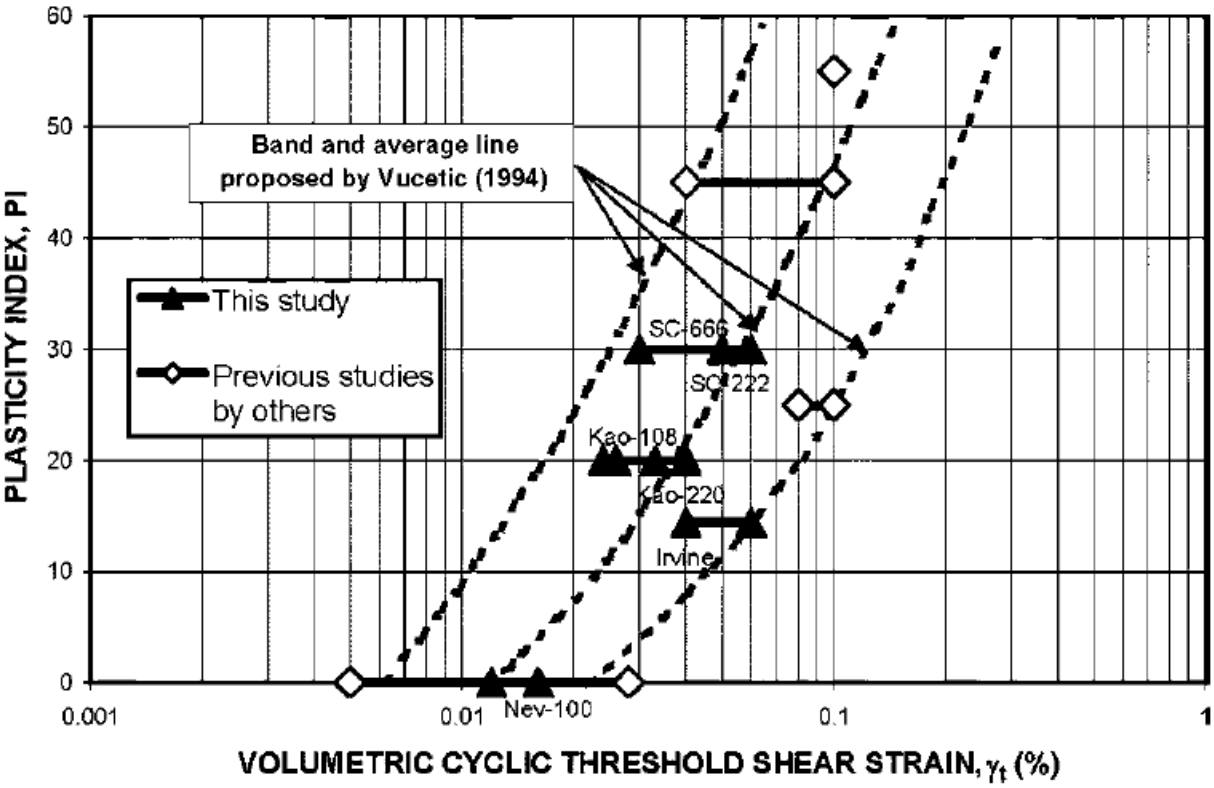


Figure 4. Correlation between threshold shear strain and plasticity index (Hsu & Vucetic, 2006).

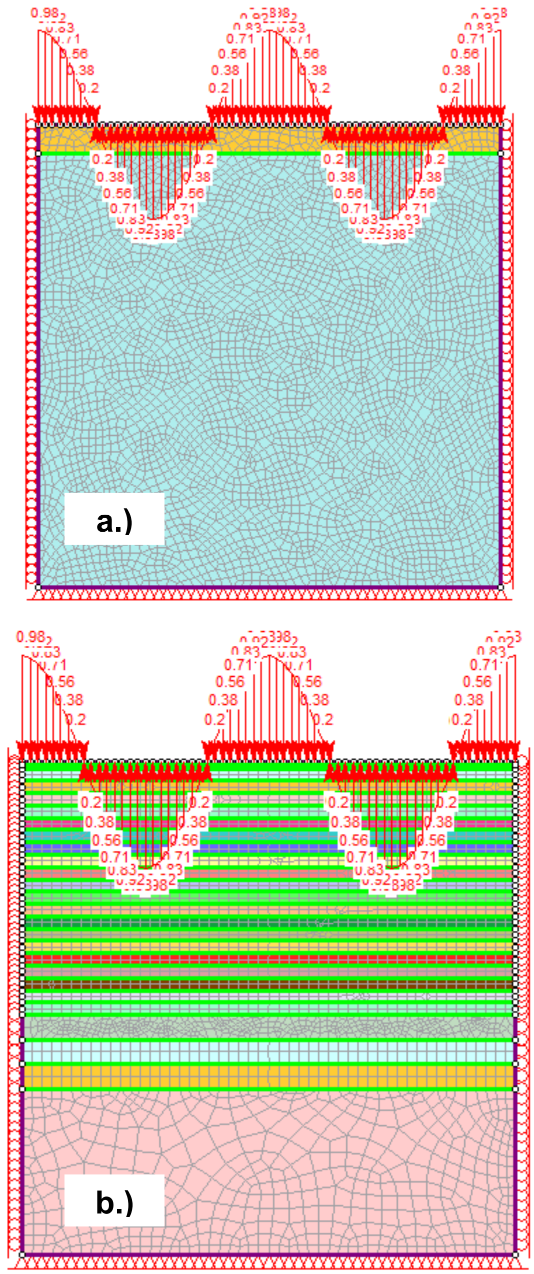


Figure 5. Finite element models developed in this study for a (a) two-layer system and (b) linear increasing shear modulus profile.

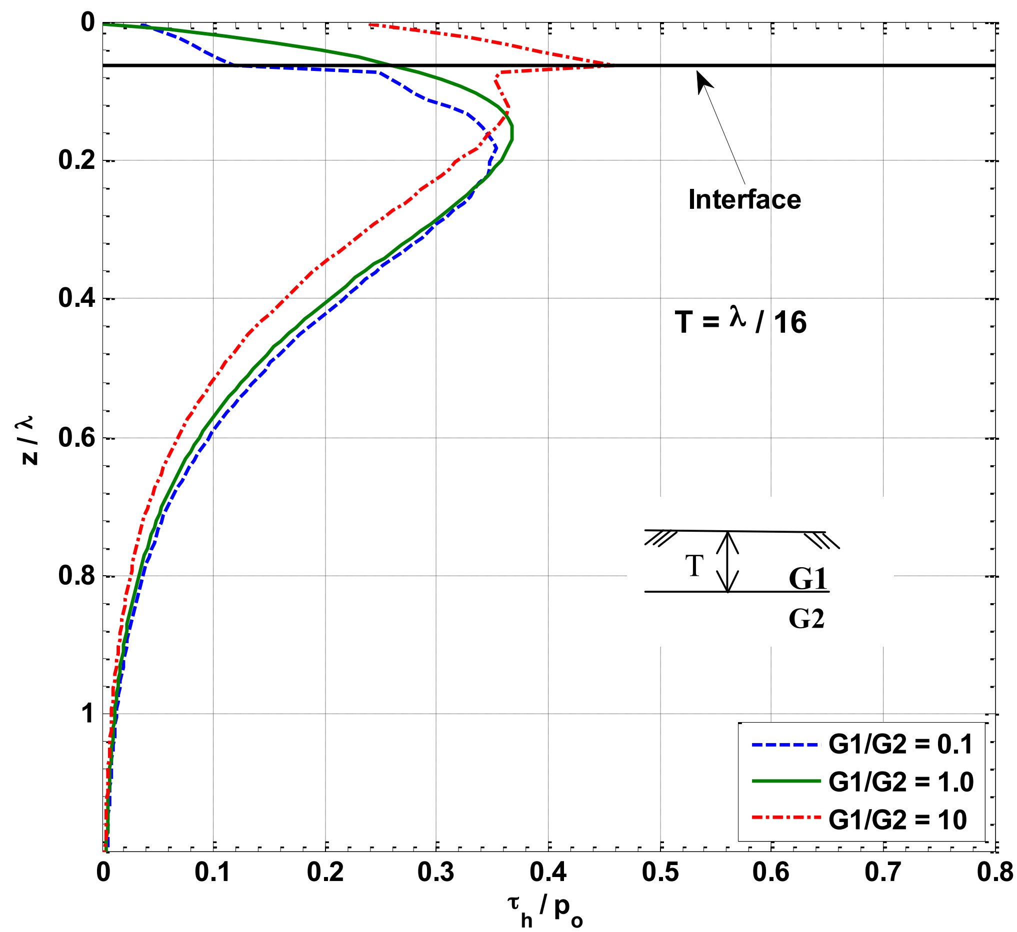


Figure 6. Normalized shear stress profile for a two-layered system (T= λ / 16).

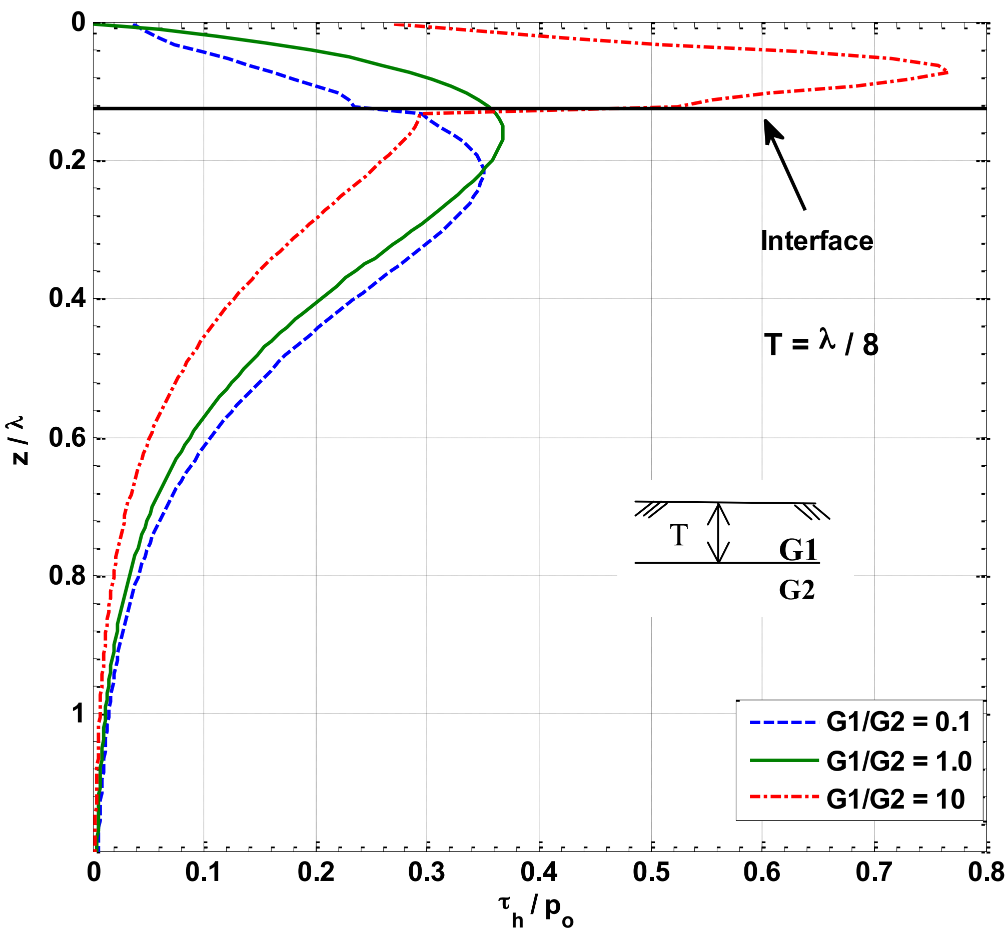


Figure 7. Normalized shear stress profile for a two-layered system (T= λ / 8).

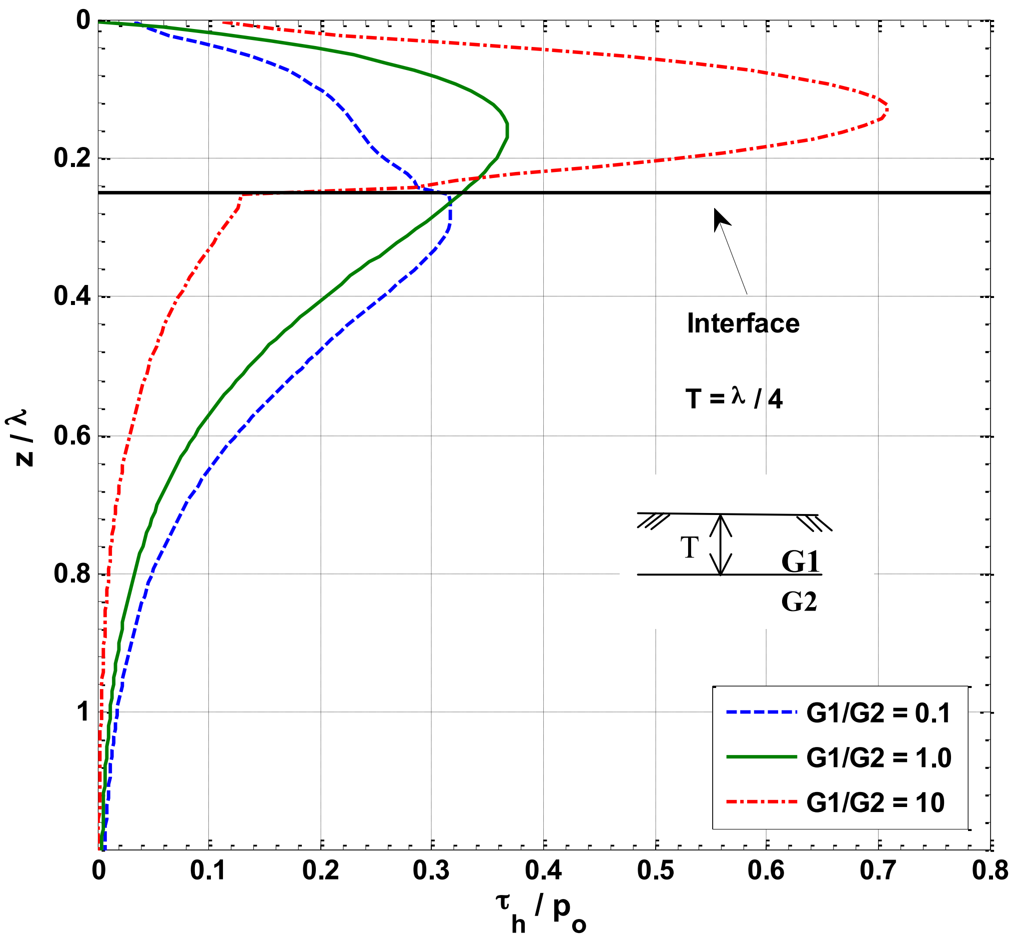


Figure 8. Normalized shear stress profile for a two-layered system (T= λ / 4).

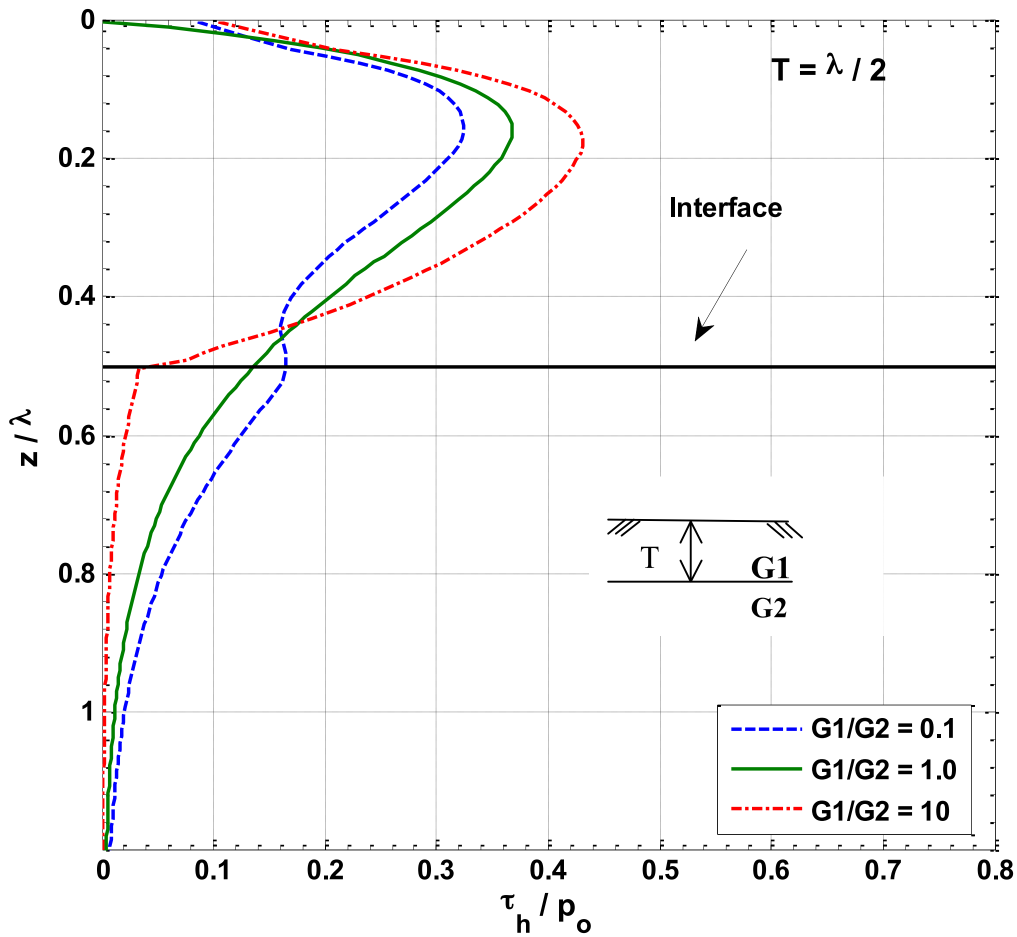


Figure 9. Normalized shear stress profile for a two-layered system (T= λ / 2).

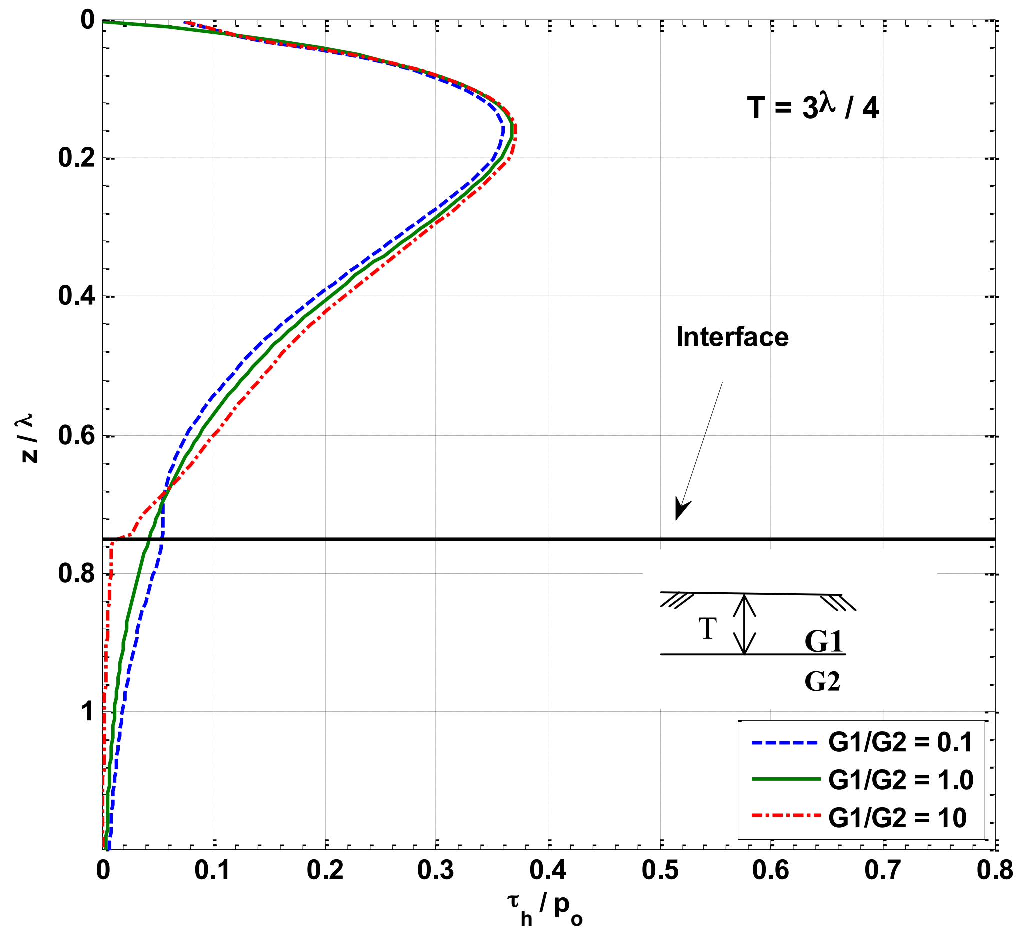


Figure 10. Normalized shear stress profile for a two-layered system (T= 3λ/4).

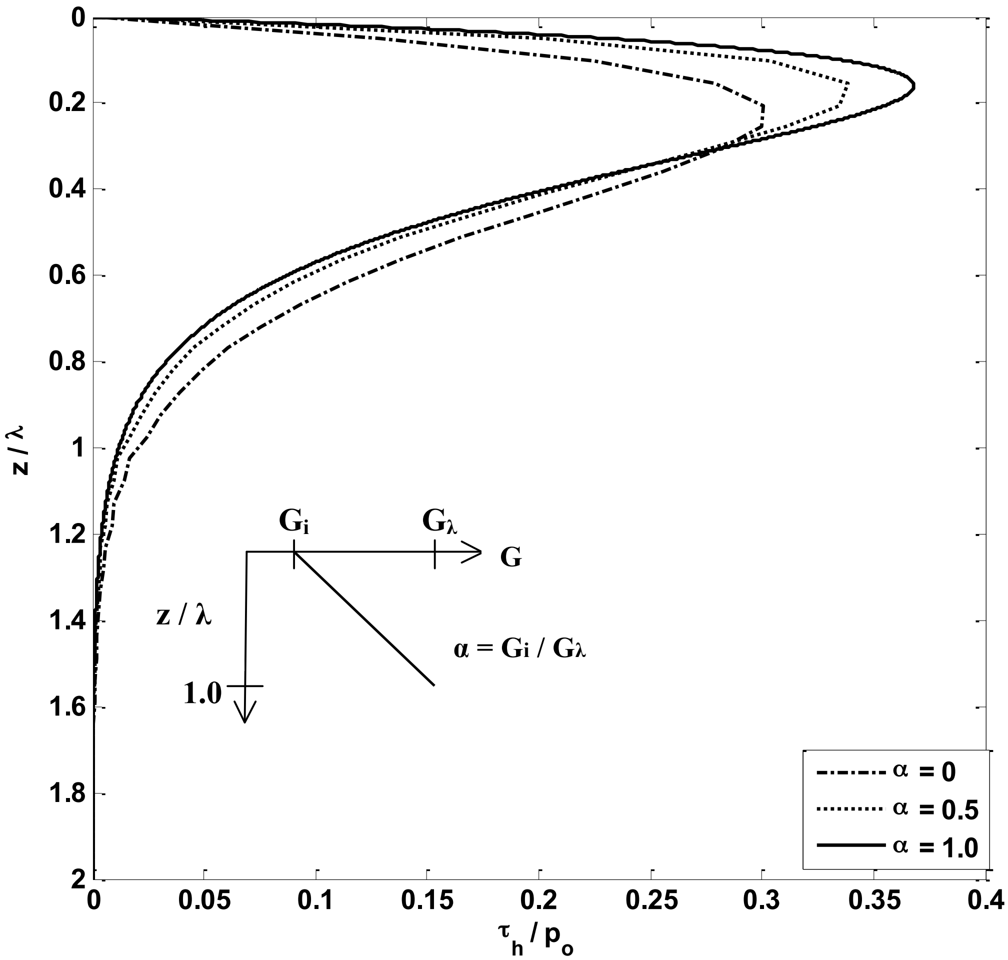


Figure 11. Normalized shear stress profile for a linear increasing shear modulus with depth.

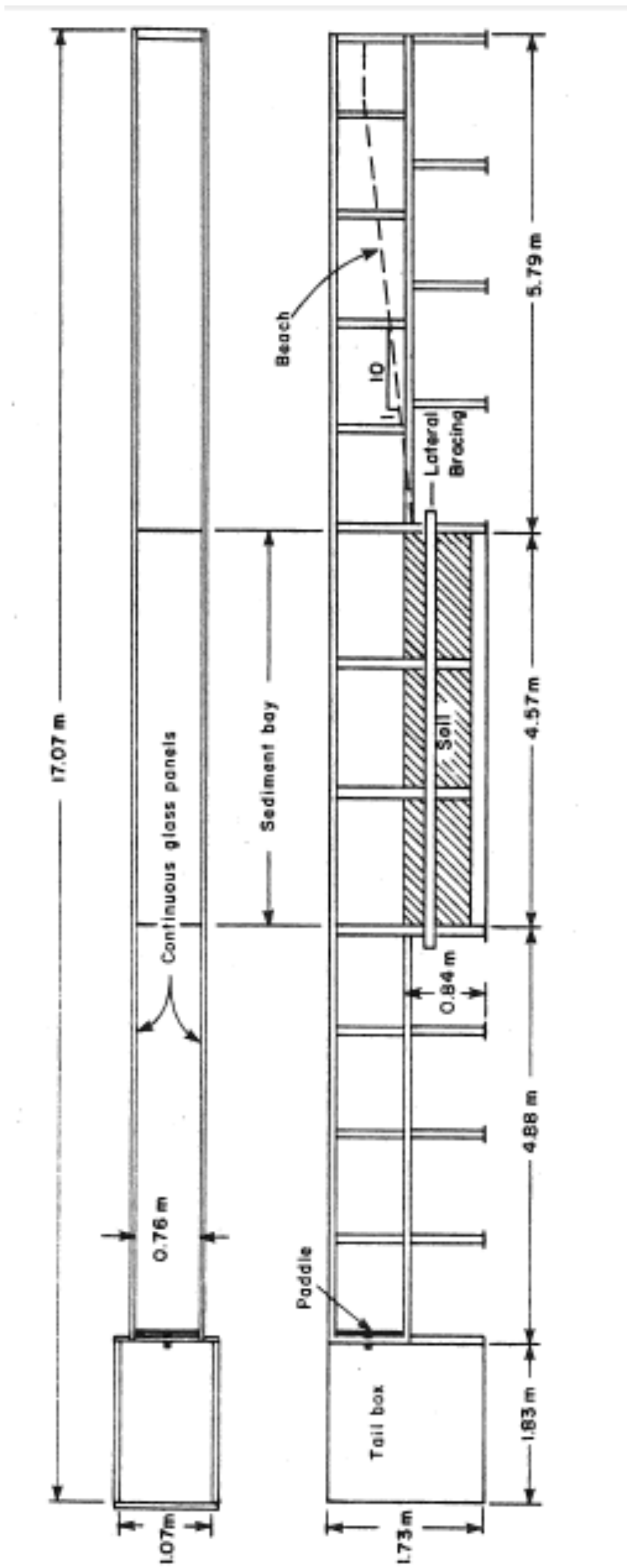


Figure 12. Facility used for the wave tank experiments performed by Clukey et al. (1985).

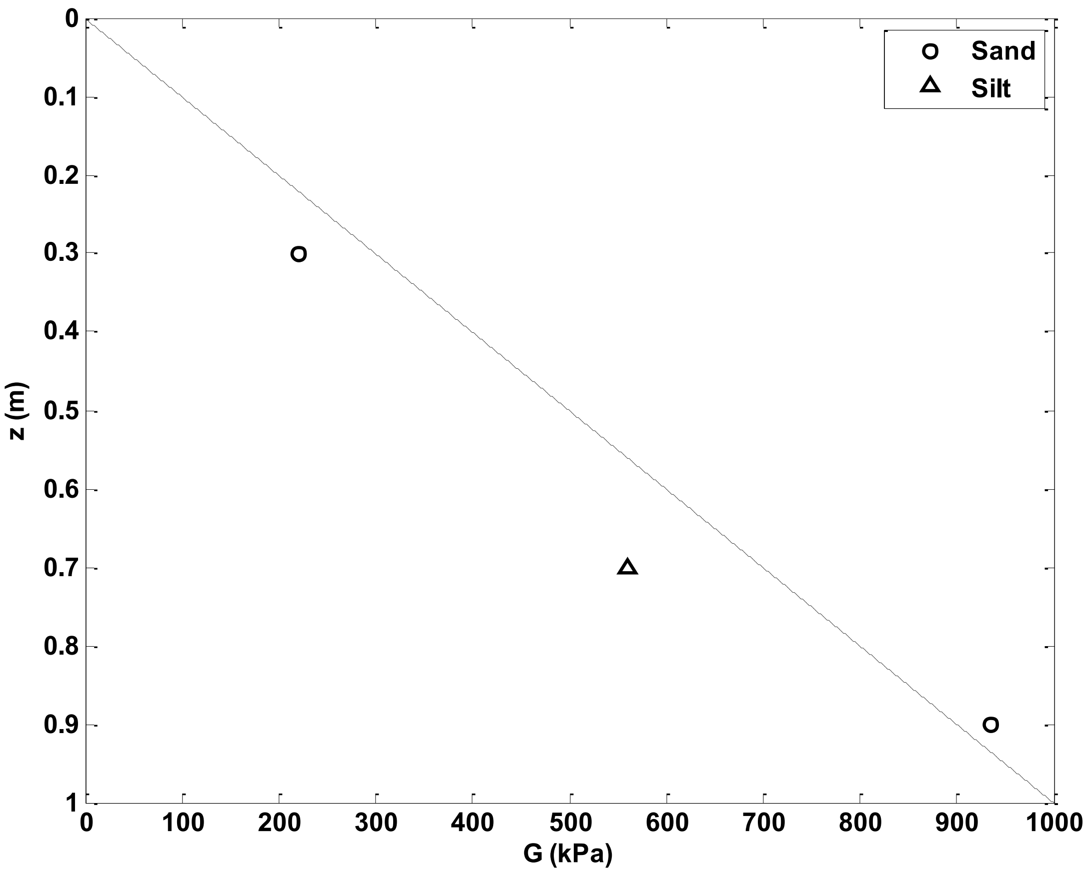


Figure 13. Shear modulus measured in direct simple shear tests performed on Danby Silt and Filter Sand under low confining stresses (data from Clukey et al. 1983).

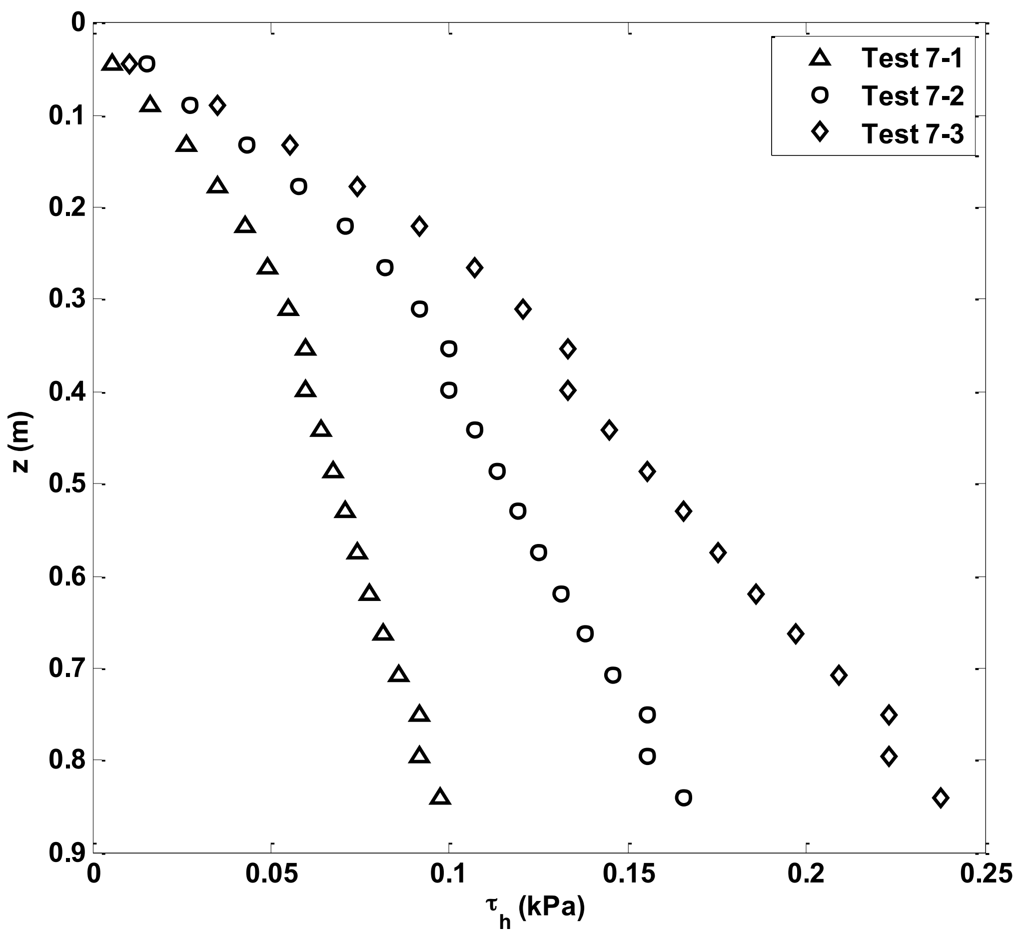


Figure 14. Estimated shear stress profiles for wave tank Tests 7-1, 7-2, and 7-3.

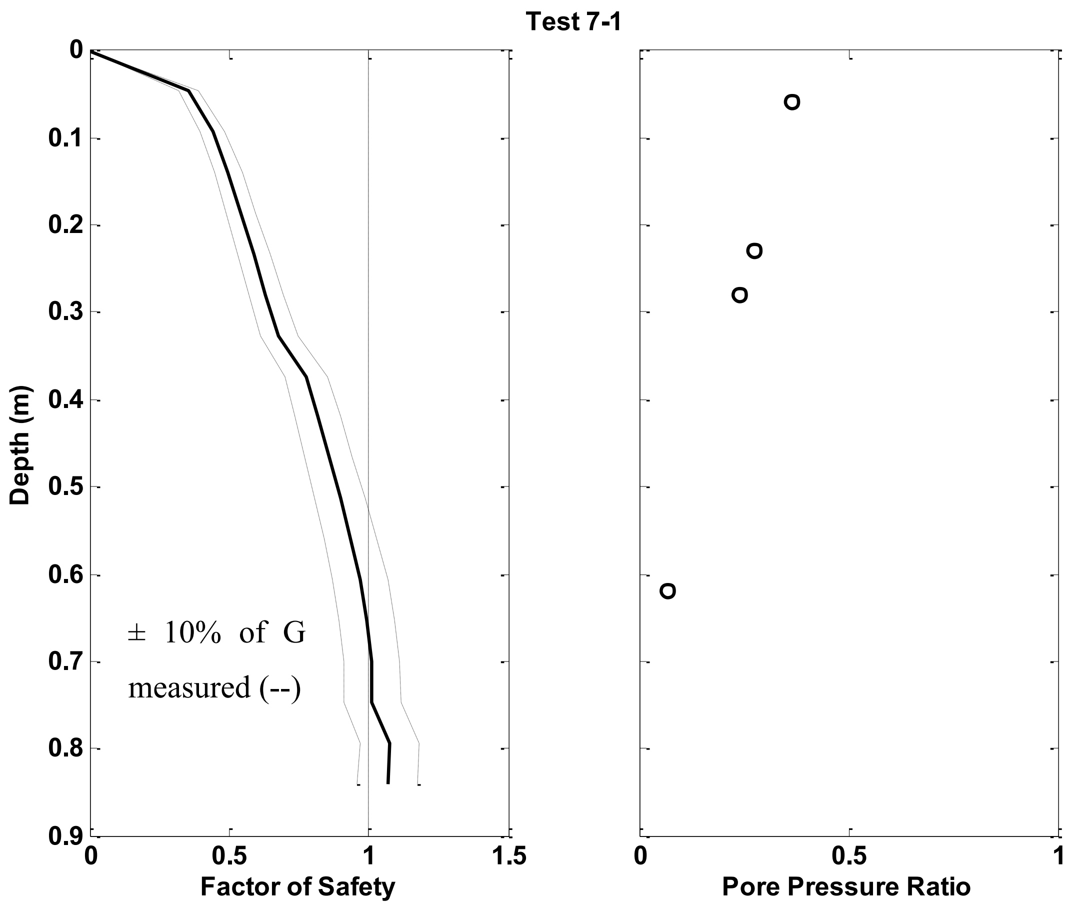


Figure 15. Modeled factor of safety and measured pore pressure ratio (Test 7-1).

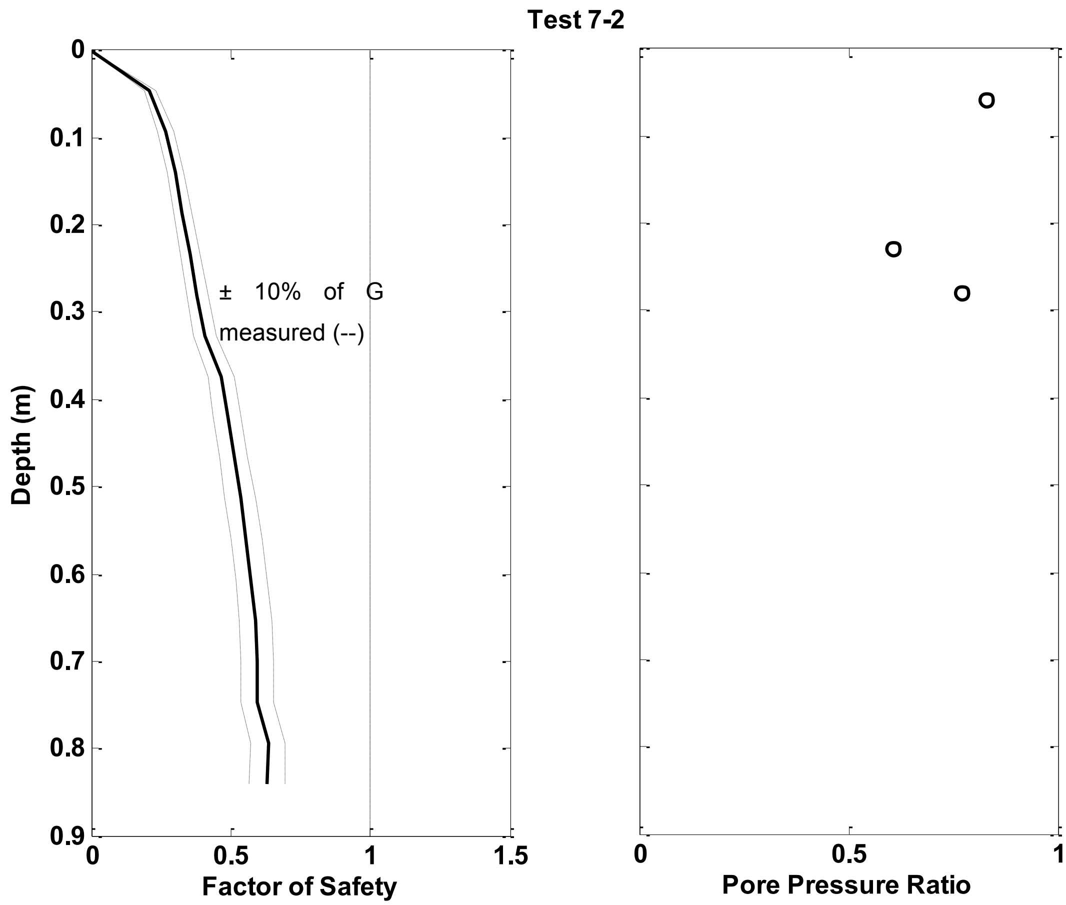


Figure 16. Modeled factor of safety and measured pore pressure ratio (Test 7-2).

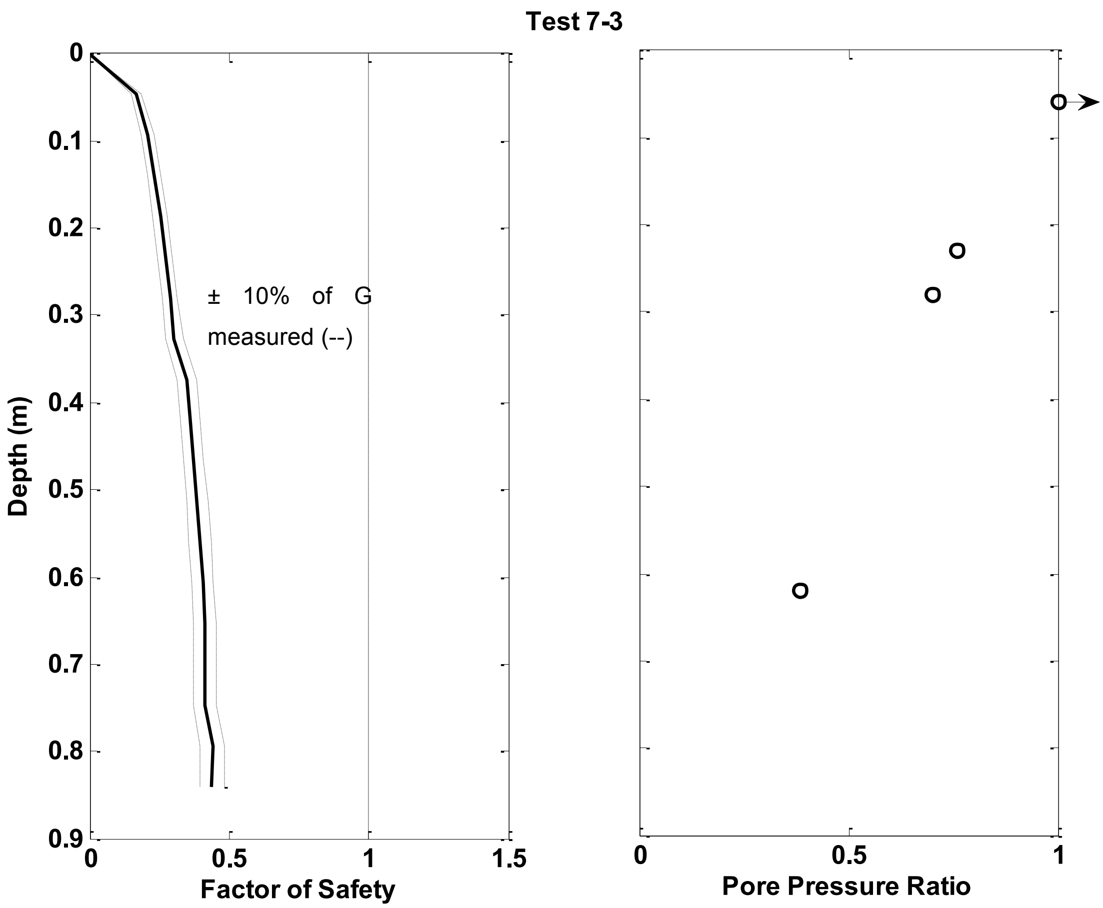


Figure 17. Modeled factor of safety and measured pore pressure ratio (Test 7-3).

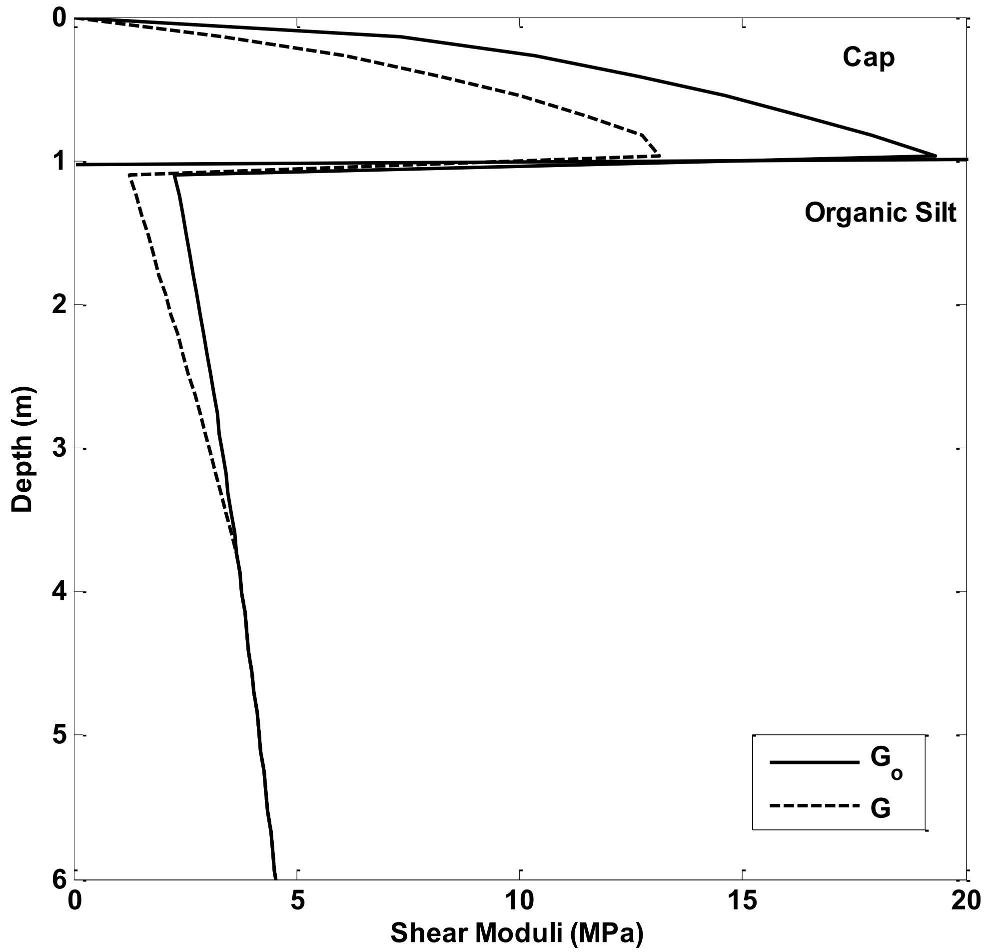


Figure 18. Shear moduli profiles calculated in the example analysis.

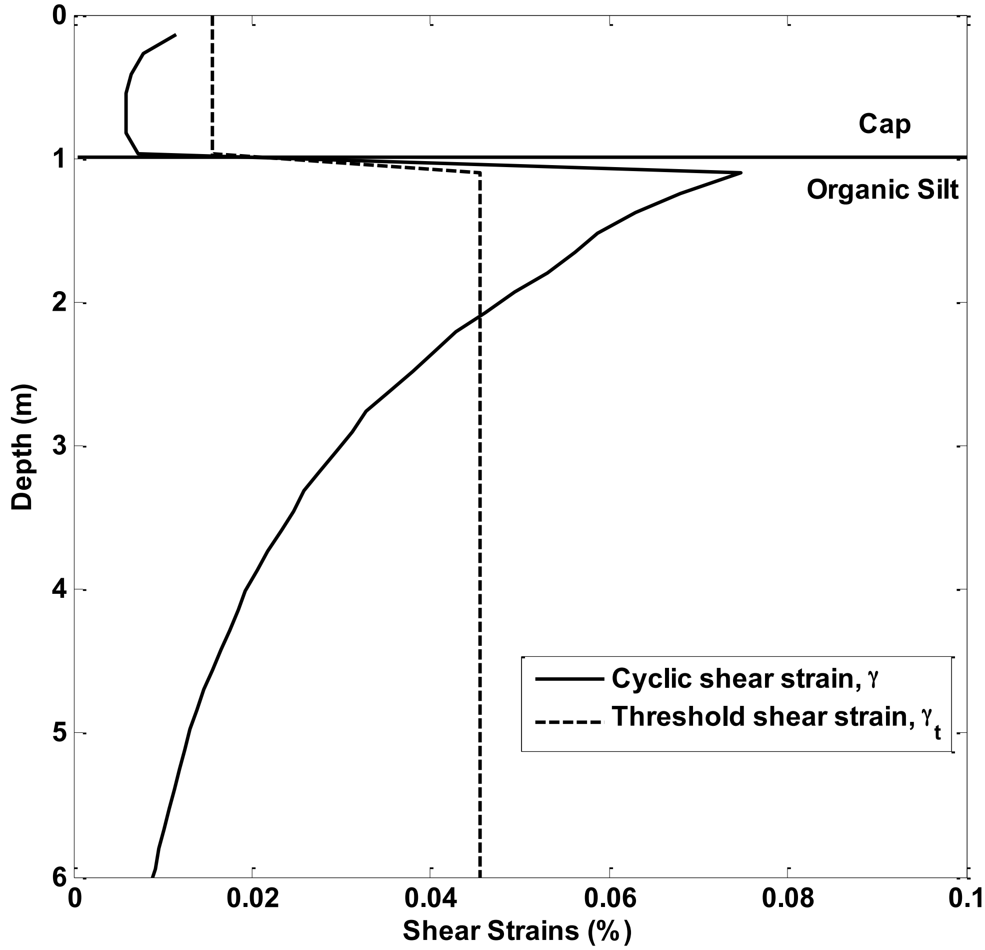


Figure 19. Shear strains calculated in the example analysis.

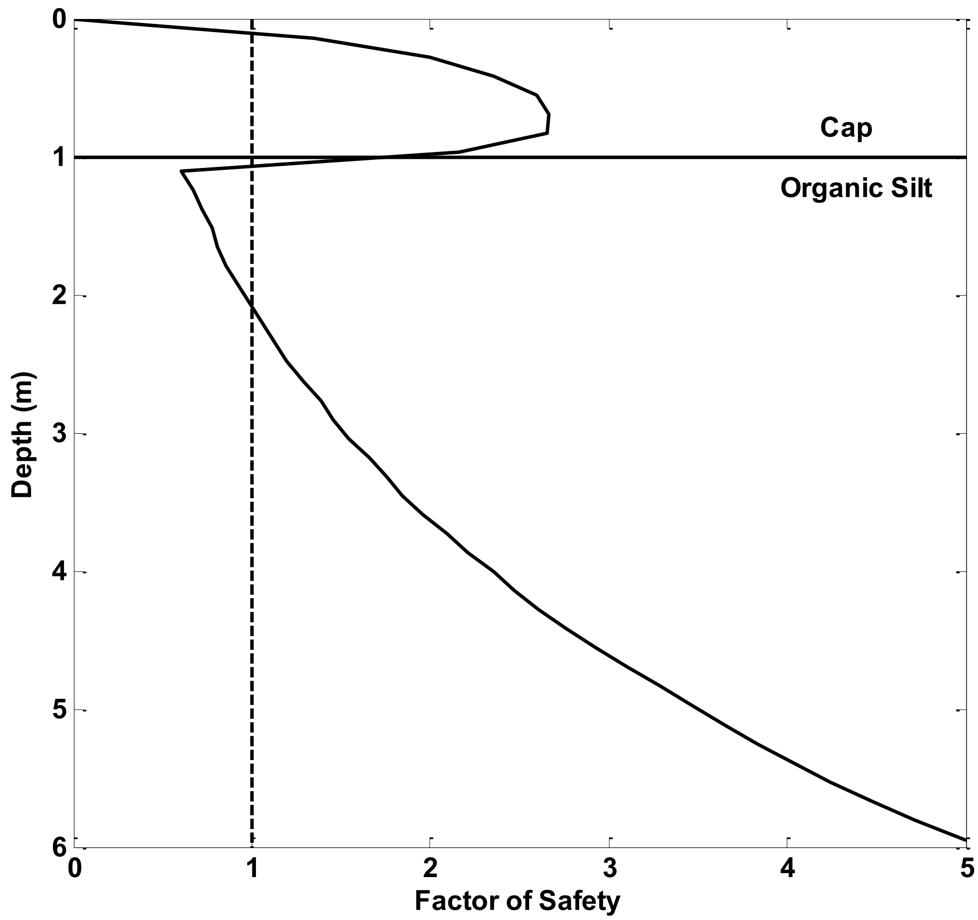


Figure 20. Factor of safety against pore pressure generation calculated in the example analysis.

Information Transfer Program Introduction

The information transfer project entitled “Clean Water Rhode Island” focused on information technology and education utilizing two major outreach activities, a comprehensive conference for the clean water community and a summer camp for high school students. Both activities had the goal of promoting interest in clean water related careers.

Clean Water Outreach in Rhode Island

Basic Information

Title:	Clean Water Outreach in Rhode Island
Project Number:	2012RI107B
Start Date:	3/1/2012
End Date:	2/28/2013
Funding Source:	104B
Congressional District:	2
Research Category:	Water Quality
Focus Category:	Education, Conservation, Water Supply
Descriptors:	
Principal Investigators:	Harold Knickle, Geoffrey Bothun

Publications

There are no publications.

Drinking Water Outreach in Rhode Island

Harold N. Knickle
Professor of Chemical Engineering
University of Rhode Island
and
Geoffrey Bothun
Associate Professor of Chemical Engineering
University of Rhode Island

Abstract

There were two goals addressed in this project. The first goal was to host a conference to: 1) disseminate knowledge to enhance the technical knowledge base of working professionals in the clean water fields and 2) educate graduate and undergraduate students in the technical aspects of the clean water field. This ongoing Rhode Island Clean Water Conference series focusing on clean drinking water issues on Rhode Island and was hosted and held at the University of Rhode Island. This year's conference was entitled "Strategic Planning for Water Resources" and was led off with a keynote presentation by Kenneth Burke chair of the RI Water Resources Board. The second goal of this project was to promote interest in clean water careers through the hosting of a summer workshop (camp) at the University of Rhode Island for middle and high school students. Camp participants were introduced to water concepts using lectures, laboratories, and field trips.

INTRODUCTION

The information transfer project entitled "Clean Water Rhode Island" focused on information technology and education utilizing two major outreach activities, a comprehensive conference for the clean water community and a summer camp for high school students to promote interest in clean water related careers.

OBJECTIVES

Two major objectives were set for this project.

1. The first was to advance the awareness and knowledge of the importance of clean water in Rhode Island and provide insight into the various factors affecting the ability to obtain clean water for multiple uses in Rhode Island by hosting a major Clean Water Conference. The creation of the conference provided background

and knowledge of the work of professionals in the clean water field. The conference has become an annual event. Graduate students were encouraged to take courses in environmental areas and undergraduates were encouraged to consider pursuing degrees related to the clean water profession.

2. The second major activity was the hosting of a summer camp at the University of Rhode Island for high and middle school students to introduce camp participants to clean water concepts with a goal of promoting interest in clean water careers.

KNOWLEDGE TRANSFER

Dissemination was an important part of this project. Results of this project were shared with all participants. A web resource was added to the Rhode Island Water Resources web site on the activities of this information transfer grant. The web based resource contains ta video of the entire conference as well as any handout material. The audiences targeted to benefit from this resource included clean water professionals, graduate, undergraduate, and high school students, faculty and administrators. These resources and be reached at www.wrc.uri.edu.

LEADERSHIP

The conference effort was guided by a steering committee. The steering committee provided guidance in choosing key speakers and presenters and hosting special break-out sessions. The steering committee consisted of students, faculty and administrators at the University of Rhode Island and representation from government and industry. Specific representation on the committee included a representative from the Providence Water Supply Board, a member of the board of the Kingston Water District, the Director of the RI Water Resources Center, the leader of the RI Pollution Prevention Center, a environmental consultant with research interests in solvent replacement for parts cleaning, an academic with interests in student learning and the principle PI of this grant.

TIMELINE

July 9, 2012 to July 13, 2012: Clean Water Summer Camp for High School Students.
November 8, 2012: Held the Clean Water Conference

SUMMER CAMP FOR HIGH SCHOOL STUDENTS ON CLEAN WATER

High school students were recruited from high and middle schools in Providence, Rhode Island to participate in the 2011 summer camp. Recruitment took place by visiting the schools and meeting with the science teachers. With their help students that demonstrated an interest in clean water careers were recruited. The schedule for the camp was from July 9 to July 13. Students started the day at 9:00 AM and completed the day at 3:30 PM. Lunch was provided by a grant from the Dean of the College of Engineering. There were no fees for this summer camp since all expenses including lunch and buses were provided to the students..

Activities included presentations of the water cycle, chemistry of water, water quality and treatment, sewage treatment using biological technology, runoff and storm water, industrial water pollution, pollution prevention, and investigation of macro-invertebrate insects present at 30 Acre Pond and health effects. Laboratory exercises and experiments included surface tension, settling measurements, turbidity measurements, water quality sampling and testing, pH and dissolved oxygen measurements, bacteria pollution testing, conductivity testing, acid rain testing, aeration, adsorption, filtration and settling treatment processes, oil spill spreading, and macro invertebrate identification and health effects. Field work included the collection of samples from various locations and water bodies. Field trips were made to a drinking water treatment facility and a sewage treatment plant as well as to the URI water supply wells and distribution on the URI campus.

Success of the summer camp was determined by two surveys, one administered at the beginning and one at the end of the camp. Each student also wrote a brief laboratory report for some of the laboratory exercises and an essay indicating the activities of most interest to each individual student.

Excellent laboratory facilities for the summer camp high school students were used at both the University of Rhode Island and in a classroom chemistry laboratory at a Providence high school. The location of the teaching facilities at the University of Rhode Island included Bliss Hall, where the environmental laboratories reside, and in Crawford Hall which houses the chemical engineering laboratories. Glassware, scales, pH and conductivity meters, chemicals and other equipment were available in these laboratories. Classrooms and computer labs were available in both building with appropriate audio-visual devices. The computer lab was used to access the web to identify bacteria in water and to use EXCEL to calculate oil spill spread on calm water. The Summer Camp Flyer is attached.

Training Potential.

The number of high school students attending was 24, 9^{th}, 10^{th} and 11^{th} grade students. These students were screened for having potential interest in having a career in clean water professions and interest in the STEM disciplines.

CONFERENCE ON CLEAN WATER

The Clean Water conference was held at the University of Rhode Island in Cherry Auditorium in the Kirk building. Invited speakers provided focus on strategic planning for Water Resources in Rhode Island.. The program is included on the next page. The presentations are on the RI Water Resources web site: www.wrc.uri.edu.

Over 31 graduate students and 60 undergraduates were in attendance and the Clean Water Conference. These students were primarily from the Civil and Environmental Engineering and Chemical Engineering disciplines. Most of the undergraduates were juniors or seniors. About 20 other professionals attended including faculty and clean water consultants. This attendance exceeded expectations.

The Cherry Auditorium was used for the conference along with the attached gallery for displays and exhibits. Coffee breaks were held the hallways surrounding the auditorium.

Final program

Clean Drinking water CONFERENCE

12:45 to 1:00pm Registration

1:00 Welcome Remarks
Dean Wright,
Dr. Thiem, Dr. Knickle

Session 1: 1:10pm to 2:00 pm

- **"Strategic Planning for Water Resources in Rhode Island"**
  Kenneth Burke, General Manager,
  RI Water Resources Board

COFFEE BREAK

Session 2: 2:15 to 3:00 pm

- **"Warwick Waste Water Treatment"**
  BettyAnne Rossi
  Pretreatment Coordinator

Session 3: 3:00 to 3:30 pm

- **"Pawtucket Water Supply"**

Chris Collins, Manager
Source Water Manager

Session 4: 3:30 to 4:00 pm

- **"Water Quality Monitoring of the Scituate Reservoir And RI Rivers"**
  Peter K. Weiskel,
  USGS

Questions and Discussion

4:00 to 4:15 pm

4:15 pm ADJOURN

Planning Committee Members
From the College of Engineering
Dr. Stanley Barnett, Dr. Donald Gray, Dr. Harold Knickle, Dr. Vincent Rose, Dr. Leon Thiem, Dr. Geoff Bothun

Sponsored by

RI Water Resources Center

www.wrc.uri.edu

Department of Chemical Engineering

www.egr.uri.edu/che

Department of Civil and Environmental Engineering

www.egr.uri.edu/cve

Conference is Free All Welcome

Refreshments Courtesy of Amgen, W Greenwich RI

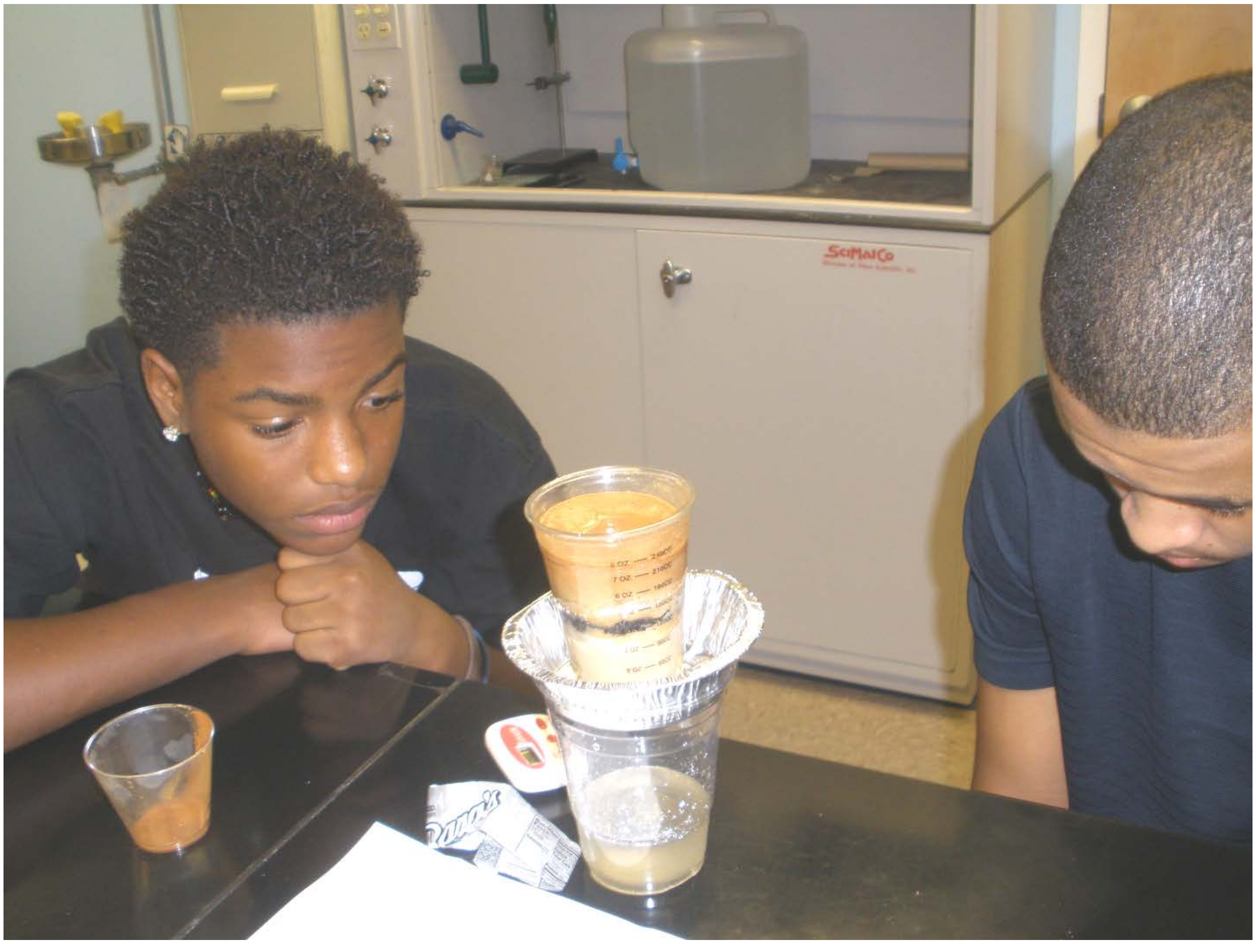
RESULTS AND BENEFITS.

The conference provided insight into the various factors affecting the ability to obtain clean water for multiple uses in Rhode Island. The breadth and depth in this project on water quality provided both awareness and knowledge to the clean water community in Rhode Island and to graduate and undergraduate students. This conference raised awareness of conservation and a broad planned approach to water supply in Rhode Island.

The hosting of a summer camp at the University of Rhode Island for high school students brought 24 students to the URI campus and provided lectures and labs on to clean water concepts with a goal of promoting interest in clean water careers.

Visit to Pawtucket Water Supply Plant

Visit to Warwick Sewage Treatment Plant



Filtration Experiment in Laboratory at URI: Student Created Sand, Gravel, Charcoal and Cotton Filtration System

Filtration, Settling Time and Turbidity Laboratory Excercise

Water Testing Activity

Analyzing Macro invertebrate sample collected at 30 Acre Pond

Analyzing Macro Invertebrate Samples from 30 Acre Pond

A Group of Students Writing Their Report on a Completed Lab Experience

Water Testing

High School Teacher, Dr. Fontaine, Receiving a Certificate for Helping with the Summer Camp

Water Testing Summer Camp

Program/Flyer for the Summer Camp on Clean Water 2012

Clean water ACTIVITIES
ALL SESSIONS 9:00 TO 3:30

Breakfast Snack and Lunch Included

Sponsored by LSAMP & URI Water Resources Center Leon Thiem, Director

College of Engineering **No person shall be denied membership because of race, color, sex, handicap, nationality, religious affiliation or belief**

URI

Summer 2012

Clean Water Engineering & Science Academy

July 9 July 13

9:00 AM to 3:30 PM

CLEAN WATER ACTIVITIES

ALL SESSIONS 9:00 TO 3:30

Breakfast Snack and Lunch Included

Session 1: Monday July 9

- Introductions and Survey
- Surface Tension: Drops on a Penny
- Water Cycle Introduction
- Settling Measurements
- Turbidity Measurements
- Intro to Water Chemistry and the Periodic Table
- Water Sample Collection
- Drinking Water Testing
- Laboratory Report

Session 2: Tuesday July 10

- Health Effects Associated With Water Quality
- Filtration and Settling
- Filtration Laboratory
- **Laboratory Report**
- **Pawtucket Water Supply Field Trip Chris Collins**

Session 3: Wednesday July 11

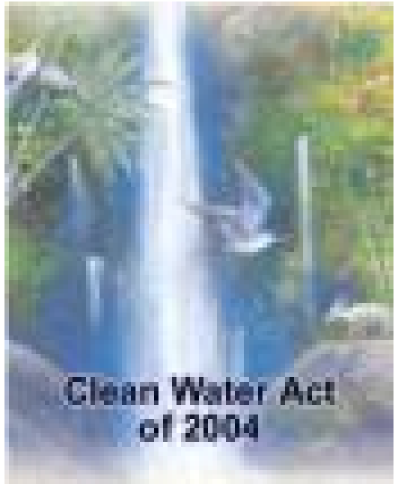
- **Dissolved Oxygen and pH**
- **Water Hardness Testing**
- **Theory of Adsorption**
- **Adsorption Measurement**
- Filtration and Settling
- Filtration Laboratory
- **Laboratory Report**
- **Water Runoff and Storm Water-Hydrology**
- Pollution Prevention.
- **Oil Spills Lab and graphs**
- **Alternate Lab**
- Video: Ponds & Rivers
- **Laboratory and Report**

Session 4: Thursday July 12

- **Rxn Time & Temperature**
- Sewage Treatment Flow Sheet
- Biology Technology
- Nitrogen and Phosphorous
- Introduction to COD,BOD
- Bacteria check 4 microbes www.google.com
- Field Trip to Sewage Treatment Plant Warwick Arrive 1:30 Ms. J. Burke

Session 5: Friday July 13

- **30 Acre Pond Sampling**
- **Macro Invertebrates**
- Introduction and Identification
- Post Assessment Survey
- Certificates



College of Engineering
Dr. H. Knickle, Professor
(knickle@egr.uri.edu)

Application to Clean Water Academy 2012

July 9 to July 13

CIRCLE YOUR INTEREST

Math Science Engineering

Name: ________________________

Address: ________________________

Telephone: ________________________

Email: ________________________

School Name: ____________________

____

Grade: ________________________

PARENTS' APPROVAL SIGNATURE

____

Return to: Dr H. Knickle, College of Engineering 874-2678, knickle@egr.uri.edu

122 Crawford Hall, Kingston, RI 02881

Clean Water Academy Summer 2011
June 27-July 1

Sponsored by URI Water Resources Center and the College of Engineering

Are you a high school student interested in math and science?

Are you interested in understanding how math and science are a key part of being an engineer?

Do you want to experience some of the fun of doing experiments?

Then you should participate in our own Clean Water Academy.

The Academy Coordinators want to help you to see just how exciting your future can be.

These **hands on** sessions will show you how interesting science and engineering can be, while you explore the options in engineering and learn valuable tools for success.

The University of Rhode Island's College of Engineering has eight undergraduate programs

There are also many physical, chemical, and biological science programs at URI.

If you decide to participate, other students will join you in the following activities:

- *Interactive workshops.*
- *Participate in real hands-on experimental activities.*
- *Interact with teachers and students from the University of Rhode Island.*

H. Knickle, PI

USGS Summer Intern Program

None.

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	3	0	0	0	3
Masters	2	0	0	0	2
Ph.D.	1	0	0	0	1
Post-Doc.	0	0	0	0	0
Total	6	0	0	0	6

Notable Awards and Achievements

The Rhode Island Water Resources Center is continuing its mission of supporting early career faculty by providing research grant funds to support a graduate student. The faculty research projects will generate data for submission to other funding agencies. The grant supported graduate students are given an opportunity to mentor with faculty as they begin their academic careers. The Rhode Island Water Resources Center outreach effort provides an opportunity for 20 middle and high school students to learn, observe and participate in clean water activities during the summer. During this camp they are encouraged to consider a career in the water field.

Publications from Prior Years

1. 2011RI97B ("Increasing sources of water supply: advanced treatment of stormwater runoff") - Conference Proceedings - Schifman L.A., V.K. Kasaraneni, T.B. Boving, V. Oyanedel-Craver. Enhanced Stormwater Contaminant Removal Using Modified Sorbents in Tree Filters. Southeastern Geological Society of America Meeting. San Juan, PR. March 20-21 2013
2. 2011RI97B ("Increasing sources of water supply: advanced treatment of stormwater runoff") - Conference Proceedings - Kasaraneni, V., Schifman, L., Boving, T., Craver, V., 2013. Enhancement of surface runoff quality using tree filter and modified sorbents. Proceeding of the ASCE World Environmental and Water Resources Congress. (EWRI), Jan. 07, 2013.
3. 2011RI97B ("Increasing sources of water supply: advanced treatment of stormwater runoff") - Conference Proceedings - Schifman, L.A., T.B. Boving, V. Craver, V. Kasaraneni. Testing a modified tree filter for its efficiency in removing PAHs from stormwater runoff in Rhode Island. 8th Annual Transportation Student Research Symposium. Storrs, CT. April 10 2012.
4. 2011RI97B ("Increasing sources of water supply: advanced treatment of stormwater runoff") - Conference Proceedings - Schifman, L.A and T.B. Boving. Sorption Capacity Of PAHs In Rhode Island Soils Along An Urban To Rural Gradient. Northeastern Geological Society of America Meeting. Hartford, CT. March 18-20 2012.
5. 2011RI97B ("Increasing sources of water supply: advanced treatment of stormwater runoff") - Conference Proceedings - Schifman, L.A., V.K. Kasaraneni, T.B. Boving, V. Oyanedel-Craver. Enhanced Stormwater Contaminant Removal Using Tree Filters And Modified Sorbents. American Geophysical Union (AGU) Fall Meeting. San Francisco, CA. December 03-07, 2012.
6. 2011RI97B ("Increasing sources of water supply: advanced treatment of stormwater runoff") - Conference Proceedings - Schifman, L.A., V.K. Kasaraneni, T.B. Boving, V. Oyanedel-Craver. Stormwater Management and Enhanced Contaminant Removal Using Tree Filters And Modified Sorbents. University of Rhode Island Transportation Symposium. Kingston, RI. October 26 2012.
7. 2011RI97B ("Increasing sources of water supply: advanced treatment of stormwater runoff") - Conference Proceedings - Kasaraneni, V.K., L.A. Schifman, T.B. Boving, V. Oyanedel-Craver. Enhancement of Surface Runoff Quality Using Tree Filters and Modified Sorbents. 2013 World Environmental & Water Resources Congress. Cincinnati, OH. May 20-23 2013.
8. 2011RI97B ("Increasing sources of water supply: advanced treatment of stormwater runoff") - Other Publications - V. Kasaraneni*, S. Kohm*, D. Ebere, T. Boving and V. Oyanedel-Craver (2013) Enhanced Containment of Polycyclic Aromatic Hydrocarbons (PAH) through Organic Modification of Soils, Environmental Progress and Sustainable Energy. DOI 10.1002/ep.11749
9. 2011RI97B ("Increasing sources of water supply: advanced treatment of stormwater runoff") - Conference Proceedings - Kasaraneni, Varun K.; Schifman, Laura A.; Boving, Thomas B.; Oyanedel-Craver, Vinka. Enhancement of Surface Runoff Quality Using Tree Filters and Modified Sorbents. New England Water Works Association annual Spring Conference & Exhibit Worcester, MA. April 2013