Characterizing the Highly Sensing Smart Piezoresistive Acrylamide Grouted Sand Using Vipulanandan Stress-Strain, Piezoresistivity and Failure Models

M. Krishnathasan and C. Vipulanandan, Ph.D., P.E.
Center for Innovative Grouting Materials and Technology (CIGMAT)
University of Houston, Houston, Texas 77204-4003.
Email: CVipulanandan@uh.edu; Phone (713)743-4278

Abstract

In this study highly sensing acrylamide polymer grouted sand was developed for potential multiple applications. The two probe monitoring method has been developed to characterize the grouted sand electrical properties and also monitor the changes with the stresses. Based on the impedance–frequency response the grouted sand was characterized as a resistance/resistivity based material. The grouted sand was tested under compression loading to evaluate the sensing properties. For the unconfined compression test the strength of the grouted sand was 350 Pa and the axial failure strain was 2% and the piezoresistive axial failure strain was over 6%, over 3 times (300%) magnification of the sensing parameter. Vipulanandan p-q stress-strain and piezoresistive models were used to predict the stress-strain behavior and also the piezoresisitive behavior of the sensing grouted sand and the models predicted the behavior very well. Also failure models, Drucker-Prager model and Vipulanandan failure model, were evaluated to represent the grouted sand behavior.

1. Introduction

Polymer grouts, also referred as chemical grouts in the literature, are used in improving the physical and mechanical properties of sand used in various applications including soil stabilization, stabilizing slopes, controlling pipe leaks and also solidifying contaminated soils. Polymer grouts are broadly characterized as organic and inorganic grouts. With the wide spectrum of applications, there is a need to make the polymer grouted soils highly sensing so that it can be monitored from the time of injection to the entire service life and also make the repaired sections highly sensing for real-time monitoring.

The first chemical grout that was used was concentrated sodium silicate, patented by Jeziorsky in 1886. After that, sodium silicate has been extensively employed in chemical grouting projects. In the past few decades various types of polymer grouts are becoming popular for various applications including gas leak and liquid seepage control (Gonzalez et al. 2005; Ozgurel 2005; Vipulanandan et al. 1986 and 2014). Also polymer grouts can be broadly classified as hydrophilic and hydrophobic. Selection of the polymer grout will depend on setting properties of the grout wit the strength or permeability related problems. To grout soils with finer grain size distributions, polymer (chemical) grouts were developed. This was because Portland cements are not applicable to conditions where fine sands exist. Polymer grouts can have viscosities similar to that of water, which allows permeation into some fine sands. Polymer grouted soils may exhibit satisfactory strength and excellent seepage control, but several issues exist with polymer grouts, such as high costs of such products and the longevity has been found less than that of cement.

2. Objectives

The overall objective of this study was to develop and characterize smart acrylamide grouted sand. The specific objectives of this study are follows:

(a) Test and quantify the monitoring electrical properties of the modified grouted sand with carbon fibers for real-time monitoring
(b) Develop and characterize the compressive stress-strain and piezoresistive behavior of acrylamide grouted sand.
(c) Model the compressive behavior of the piezoresistive acrylamide grouted sand and also failure strength of grouted sand.

3. Materials and Methods

In this study grouted sand specimens were prepared using the acrylamide (water soluble) grout.

Acrylamide Grout

In this study, commercially available acrylamide AV-100 (Avanti International, Texas) was used and the solution had viscosity comparable to water. It is a water soluble grout. In order to polymerize the grout solution, catalysts and activators were used. The activator used was triethanolamine (TEA) which polymerizes the grout. The catalyst used was ammonium persulfate which triggers the polymerization reaction.

Sand

Silica sand was characterized based on the particle size distribution. The d_{50} for the sand was 0.26 mm. The d_{90} was 0.47 mm and d_{10} was 0.09 mm. It was characterized as uniformly graded sand.

Grouted Sand Samples Preparation

All the grouted sand specimens were prepared in split cylindrical Teflon molds 10.2 cm (4 in.) in length and 3.8 cm (1.5 in.) in diameter. Teflon filters were used at the bottom and top of the molds. Moreover to prevent grout leakage during injection from the split molds silicon was applied along the split groves to the outside of the molds. The grout was injected from the chamber into the sand filled molds (Fig. 1). Conductive fillers were added with the sand before grouting. Grout solution was injected from the bottom of the molds for 1 min. under a pressure of 7 kPa (1 psi). To obtain fully grouted sand specimens, grout was allowed to flow through the column until no air bubble was observed in the outflow tube. Also the four wires were used to monitor the electrical property changes along the length and across the diameter.

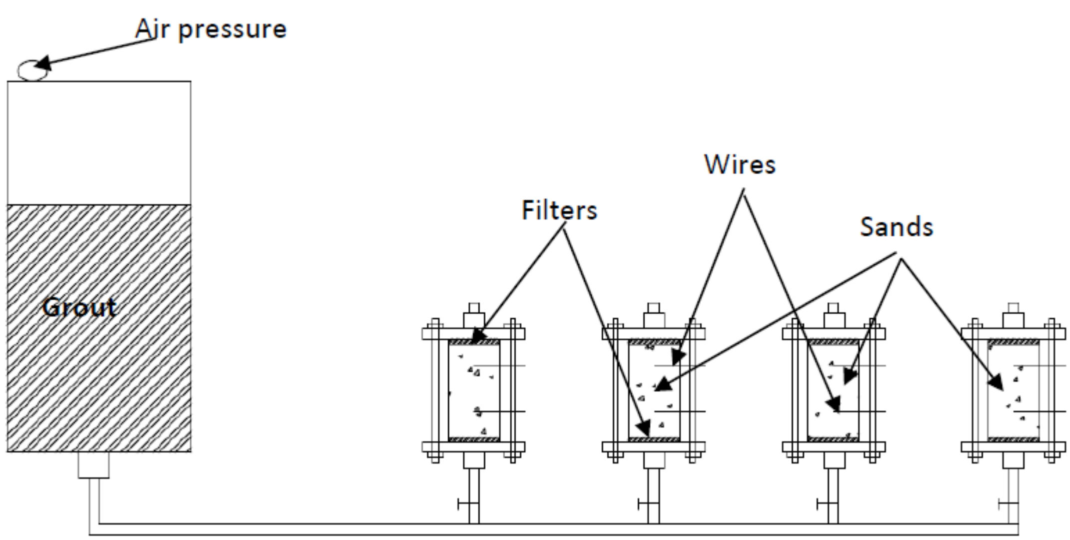

Figure 1. Setup for Preparing the Grouted Sand Specimens

Compression Test
Grouted sand specimens were tested in uniaxial compression using the CIGMAT GR2-02 standard.

Piezoresistivity Test

Piezoresistivity means that the change in electrical resistivity under applied stress. In this study acrylamide grouted sand was investigated and characterized. Piezoresistivity of acrylamide grouted sand in axial compression was investigated with varying amount of Conductive filler (CF) by the weight of the sand. In this study, impedance frequency relationship was investigated to characterized grouted sand in terms of electrical properties using the LCR (L-inductance; C-capacitance; R- resistance) meter up to a frequency of 300 kHz (Vipulanandan et al., 2013).

Models

Stress-Strain Model

In order to predict the behavior of acrylamide grouted sands for stress-strain relationship, The Vipulanandan p-q stress-strain model was used. The model is defined as follows:

$$\sigma = \left[\frac{\frac{\varepsilon}{\varepsilon_c}}{q + (1 - p - q)\frac{\varepsilon}{\varepsilon_c} + p\left(\frac{\varepsilon}{\varepsilon_c}\right)^{\frac{(p+q)}{p}}} \right] \sigma_C \quad (1)$$

where, p and q are the material parameters, σ_c and ε_c defines the peak stress and strain respectively. Parameter "q" represents as the ratio of secant modulus to initial modulus. Parameter p represents the optimization parameter which is calculated by minimizing the error in estimating the relationship.

Vipulanandan p-q Piezoresistivity Model

In order to predict piezoresitivity behavior of acrylamide grouted sand, Vipulanandan piezoresistivity p-q model (Vipulanandan et al., 2014-2016) model was used. The model is as follows:

$$\sigma = \frac{\sigma_{max} x \left(\frac{\left(\frac{\Delta\rho}{\rho}\right)}{\left(\frac{\Delta\rho}{\rho}\right)_0} \right)}{q_2 + (1 - p_2 - q_2) x \left(\frac{\left(\frac{\Delta\rho}{\rho}\right)}{\left(\frac{\Delta\rho}{\rho}\right)_0} \right) + p_2 x \left(\frac{\left(\frac{\Delta\rho}{\rho}\right)}{\left(\frac{\Delta\rho}{\rho}\right)_0} \right)^{\left(\frac{p_2+q_2}{p_2}\right)}} \quad (2)$$

where, σ_{max} represents the maximum stress at failure, $(\Delta\rho/\rho)_0$ is the piezoresistive strain of the acrylamide grouted sand under peak stress, $(\Delta\rho/\rho)$ is the piezoresistive strain at any stress and p_2 and q_2 are material parameters.

4. Results and Analyses

Grouted sand specimens ware prepared with vary CF contents and was cured under room condition and tested after 10 days.

Material Characterization

The grouted sand with varying amount of conductive fibers (carbon or basaltic) (CF) were tested to identify the electrical property to monitor. The CF was varied up to 1% and optimum results are presented. The impedance-frequency response of grouted sand with 0.03% CF is shown in Figure 2. It clearly identified the behavior as CASE-2, representing resistivity as the material property (Vipulanandan et al. 2013). Also resistivity is independent of the frequency but in study measurements will be made at 300 kHz to eliminate the contact resistance and impedance so that the bulk material property can be measured directly (U.S. patent 2019 and 2020).

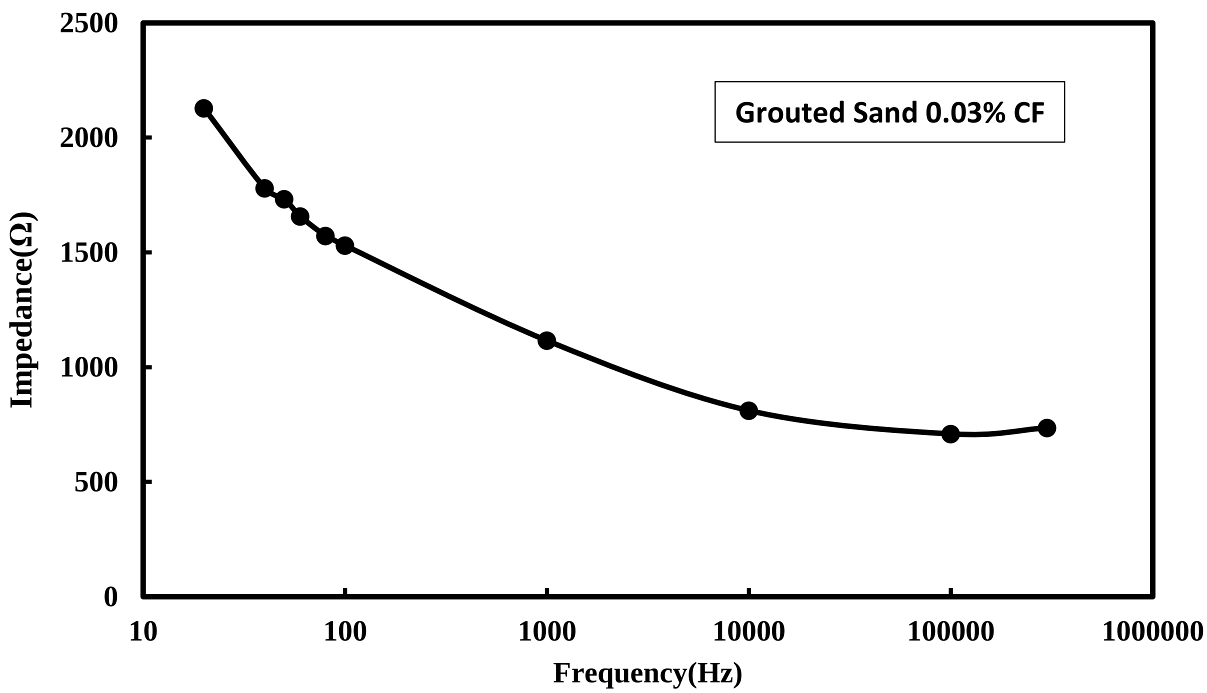

Figure 2 Impedance –Frequency response of grouted sand with 0.03% CF

Compression Behavior

Stress-strain

The typical stress-strain relationships for the grouted sand is shown in Figure 3 and Vipulanandan p-q stress-strain model was used to predict the behavior. The grouted sand with 0.03%CF had a strength of 470 kPa compared to 373 kPa for 0.06% CF grouted sand, about 21% reduction in strength. Strain at ultimate compressive strength was 0.018 (1.8%) and 0.03 (3%) for 0.03% CF grouted sand and 0.06% CF grouted sand respectively, 66% higher strain tolerance. Also the p and q model parameters are summarized in Table 1.

Piezoresistivity

The resistivity increased with the applied compressive stress. The piezoresistive response of grouted sand with 0.03% CF and 0.06% CF is shown in Figure 4. The piezoresistive axial strain at peak stress for the grouted sand with 0.03% CF was 7.3% as shown in Figure 4, over 4 times (400%) higher than the compressive strain of 1.8%. The piezoresistive axial strain at peak stress for the grouted sand with 0.06% CF was 6.7%, 2.2 times (220%) higher than the compressive failure strain of 3%. The results show the piezoresistive sensitivity of acrylamide grouted sand.

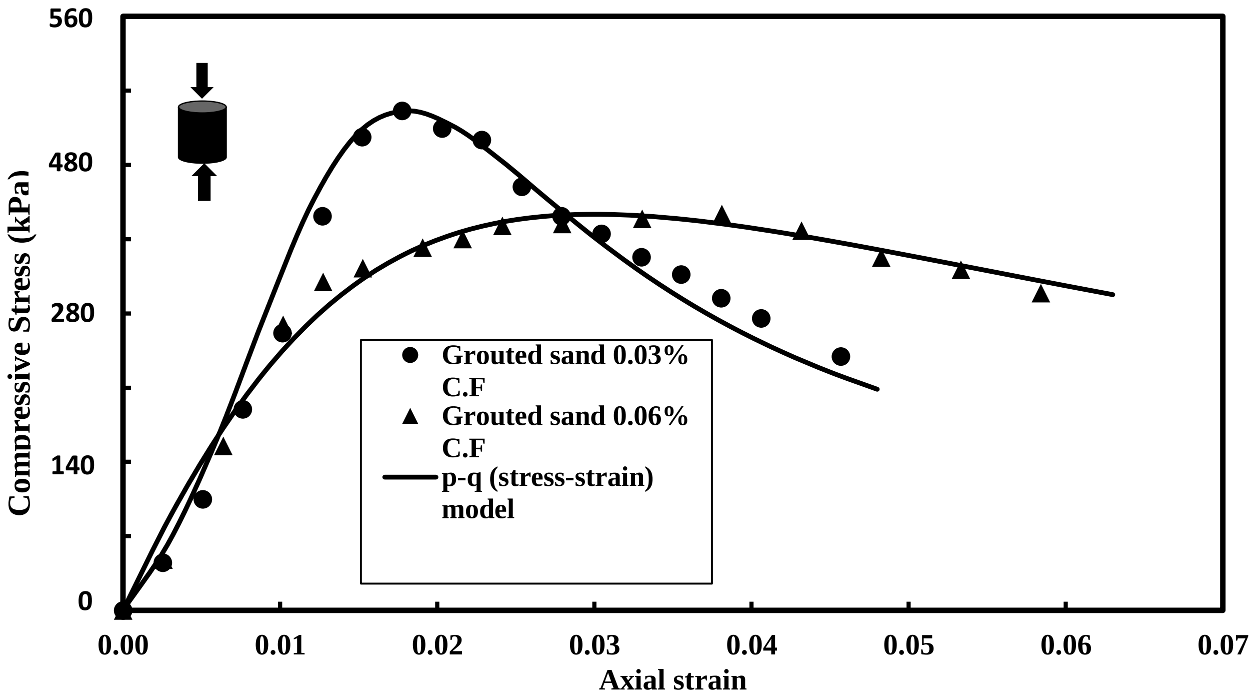

Figure 3 Measured and Predicted Stress-Strain Relationship for Grouted Sand

Table 1. Vipulanandan p-q stress strain model parameters for grouted sand under compression

Specimen	p	q	σ_c (kPa)	ε_{max}	R^2	RMSE (kPa)
Grouted sand 0.03% C.F	2.03	1.52	470.4	0.018	0.97	21.7
Grouted sand 0.06% C.F	0.34	0.39	373.1	0.030	0.99	13.3

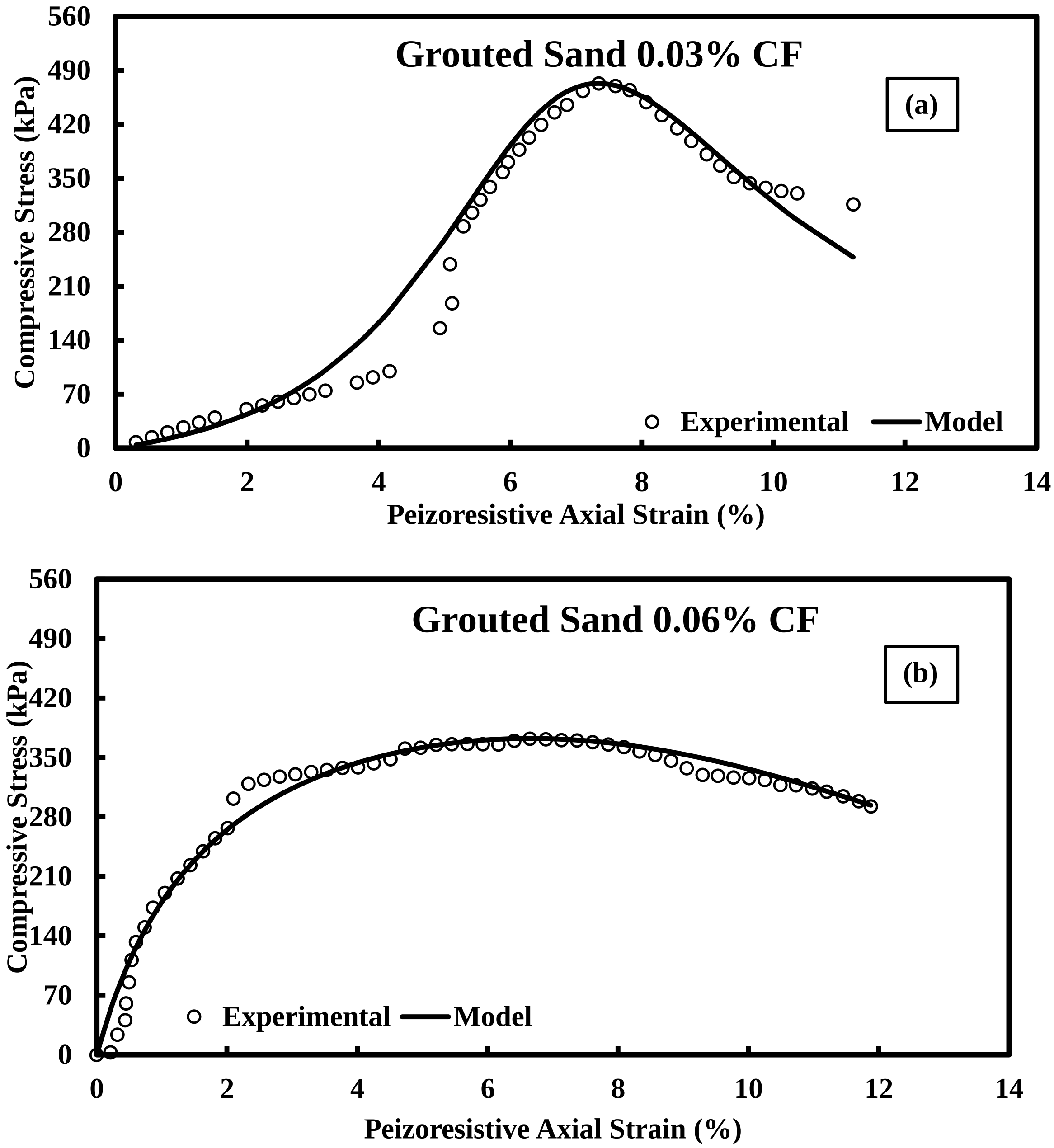

Figure 4 Measured and Predicted Stress-Piezoresistive-Strain Relationship for Grouted Sand (a) 0.03% CF and (b) 0.06% CF

Failure Model

It is important to identify the critical stress parameters for the three dimensional failure model. Where First stress invariant (I_1) and second deviatoric stress invariant (J_2) defined as follows:

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \tag{6}$$

$$J_2 = \frac{1}{6}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \tag{7}$$

Where $\sigma_1, \sigma_2, and\ \sigma_3$ are the major principal stress at failure, intermediate principal stress and minor principal stress respectively.

Drucker–Prager Failure Model (1950)

Drucker–Prager criterion has been widely adopted for the modeling of confined concrete because of its simplicity (involving only two parameters) and its capability to capture shear strength increases as per result of hydrostatic pressure increases, which is a unique property of concrete under confinement.

Mohr-Coulomb failure surface has corners on the hexogen which is not mathematically convenient. Drucker and Prager have smoothened the Mohr-Coulomb by simple modification of Von Mises criterion. According to Drucker and Prager model $\sqrt{J_2}$ increases linearly with the increase of principal stresses and the Model equation is as follows:

$$\sqrt{J_2} - \alpha I_1 - K = 0 \tag{8}$$

Where I_1 is the sum of normal stresses (first stress invariant), J_2 is second deviator stress invariant and α and K are material constants.

. When $$\boldsymbol{I_1 \rightarrow \infty, \text{then} \sqrt{J_2} \rightarrow \infty} \tag{9}$$

There is a limit to shear tolerance for the grouted sand materials and hence, Drucker–Prager model doesn't satisfy this condition.

Vipulanandan Failure Model (2018)

The Vipulanandan failure relationship (Eqn. (10)) satisfying all the basic conditions is as follows (Vipulanandan et al. 2018)

$$\boldsymbol{\sqrt{J_2} = \tau_0 + \frac{I_1}{L + N I_1}} \tag{10}$$

Hence, this model has a limit on the maximum shear stress the concrete will tolerate at relatively high mean stress.

$$\boldsymbol{\sqrt{J_2}_{max} = \tau_0 + \frac{1}{L} \quad \text{When} \quad I_1 \rightarrow \infty} \tag{11}$$

Vipulanandan failure model will represent the Drucker and Prager model when B = 0 and the Von Mises Criterion when A = 0, a generalized failure model. Vipulanandan failure model will represent the Drucker and Prager model when B = 0 and the Von Mises Criterion when A = 0, a generalized failure model.

Model Verifications

Grouted sand specimens were tested in uniaxial compression and also splitting tension. Splitting tension test will represent biaxial stress condition on the failure plane (Davis and Bose (1968). Using the 20 test data the failure of the acrylamide grouted sand was investigated and the two models are compared in Fig. 9. The Drucker–Prager and Vipulanandan model parameters and

R^2 and RMSE are summarized in Table 5. Based on the statistical parameters, Vipulanandan failure model predicted the test results better than the Drucker-Prager model.

Table 5. Summary of Failure Model Parameters

Drucker-Prager Linear Model				Vipulanandan Model					
Slope (α)	K (kPa)	R^2	RMSE (kPa)	L	N $(kPa)^{-1}$	$(\sqrt{J_2})_o$ (kPa)	$(\sqrt{J_2})_{max}$ (MPa)	RMSE (kPa)	R^2
0.65	124	0.74	159	0.86	0.00035	0.0	2751	137	0.80

5. Conclusions

Based on this experimental and analytical study the following conclusions are advanced:

1. Based on the material characterization, resistivity was proven to be the electrical property of the acrylamide grouted sand. Monitoring at 300 kHz will eliminate the effects of the probes used for monitoring. Vipulanandan p-q model predicted the stress-strain and piezoresistivity behavior of acrylamide grouted sands.
2. Smart piezoresistive grouted sand has been developed and verified under compression and splitting tension loading. Adding 0.03% conductive fiber (carbon or basaltic) made the optimum piezoresistive acrylamide grouted sand..
3. Vipulanandan p-q stress-strain and piezoresistive models predicted the stress-strain and piezoresistivity behavior of acrylamide grouted sands.
4. Vipulanandan failure model predicted the data well compared to the Drucker-Prager model.

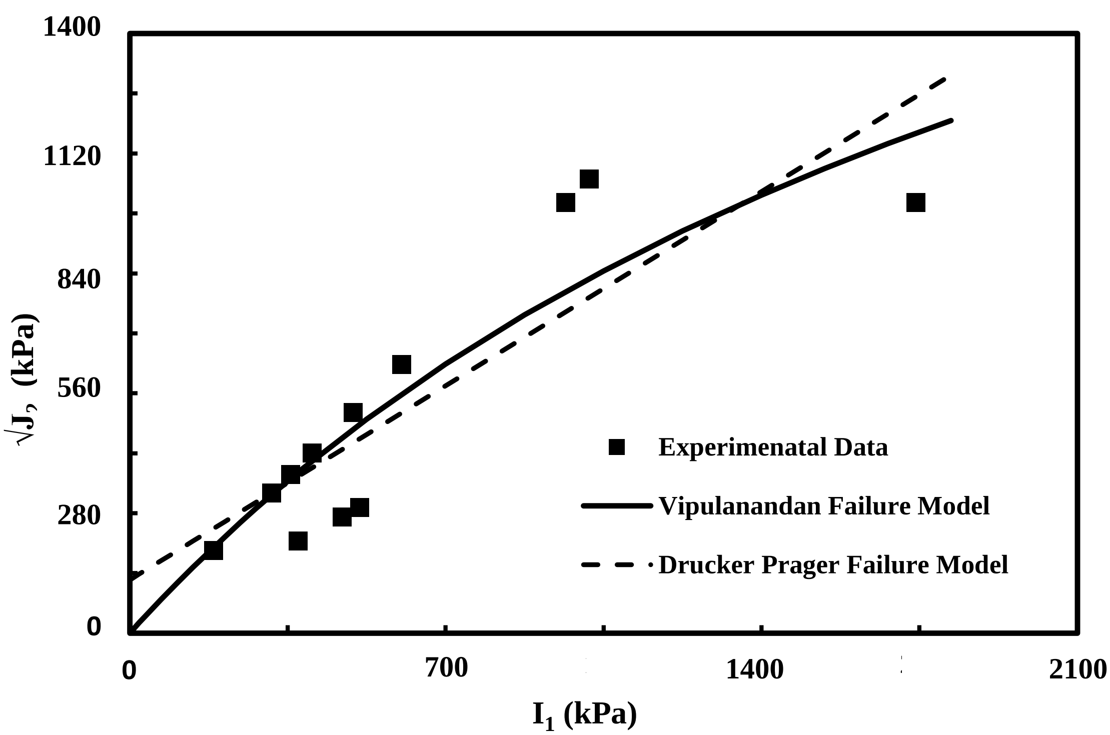

Figure 5 Measured and Predicted Stress-Piezoresistive Strain Relationship for Grouted Sand

6. Acknowledgement

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7. Reference

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