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Monitoring and groundwater/gas sampling in sands densified with explosives

Monitoreo y muestreo de aguas subterráneas y gases en arenas densificadas con explosivos

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Abstract
This paper presents the results of a blast densification field study conducted at a waste disposal landfill located in South Carolina, United States, to determine the type of gases released and their in-situ concentrations in the ground after blast densification. The BAT probe system was used to collect groundwater and gas samples at the middle of the targeted layer and to measure the porewater pressure evolution during and after the detonation of the explosive charges. In addition, standard topographic surveys along the centerline of the tested zones were conducted after each blast event to quantify the effectiveness of the blast densification technique to densify loose sand deposits. The results of this study show that: a) the BAT probe system is a reliably in situ technique to collect groundwater and gas samples before and after blasting; b) the soil mass affected by the detonation of the explosives fully liquefied over a period of 6 hours while the in-situ vertical effective stresses returned to their initial values after about 3 days; and c) significant induced vertical strains were observed in the blasting area after each detonation, indicating that the soil mass has been successfully densified.

Keywords: Blast densification, gassy soils, BAT probe, densification, loose sands, liquefaction.

Resumen
Este manuscrito presenta los resultados de un estudio de densificación de suelos en campo utilizando explosivos y realizado en un relleno sanitario localizado en Carolina de Sur, Estados Unidos; este estudio se realizó con el objeto de determinar los tipos de gases que se liberan y sus respectivas concentraciones in situ después del proceso de densificación. Se utilizó un sistema de sonda BAT para recolectar las muestras de aguas subterráneas y de gas en la mitad del estrato en estudio, así como para medir la evolución de las presiones del agua durante y después de la detonación de las cargas explosivas. Adicionalmente, se hicieron mediciones topográficas a través del eje central longitudinal de la zona de estudio después de cada explosión para medir la magnitud y la efectividad de esta técnica de densificación en depósitos de arena sueltas. Los resultados de este estudio mostraron que: a) el sistema de sonda BAT puede ser una técnica confiable para recolectar muestra de agua subterránea y gas en campo antes y después de la explosión; b) la masa de suelo afectada por la detonación de los explosivos licuó por un periodo de 6 horas, mientras el esfuerzo vertical efectivo alcanzó sus valores iniciales después de 3 días; y c) se observaron deformaciones verticales significativas en el área de estudio después de cada explosión, lo cual indica que la masa de suelo fue exitosamente densificada.

Palabras clave: Densificación con explosivos, suelos gaseosos, sonda BAT, densificación, arenas sueltas, licuación.

1. Introduction

Blast densification has been used for more than 70 years to densified loose and saturated sand deposits. This technique is commonly used to densify large areas of loose sand deposits and thus increase the strength and liquefaction resistance of the soil. During this process, large amounts of gas are produced and released in the ground. These gasses may remain trapped in the ground for months or even years [1-3].

Because gas in free form or dissolved in the pore fluid increases the pore fluid compressibility [4] and significantly affects the mechanical response of the soil [5-9], it is important to determine the type of gases produced by typical explosives and quantify their in-situ concentrations. For loose sands which exhibit strain softening responses during undrained shear, and thus are susceptible to liquefaction and flow, the effect of gas in the sample is to change the responses from softening to hardening as the amount of gas in the soil increases [8]. For dense sands the presence of gas has the effect of reducing the "undrained" shearing resistance of sands [7]. The amount of hardening decreases as the amount of free gas increases.

This paper presents the results of a field investigation study conducted at a waste disposal landfill located in South Carolina, United States, to determine the type of gas present in the soil and quantify their in-situ concentrations after the sand has been densified with explosives. For this study, a BAT sampling system was adopted to collect pressurized samples at the middle of the blasted layer and to monitor the porewater pressure evolution after blasting. The results show that the BAT probe system is a suitable technique to collect groundwater and gas samples, and the blast densification technique is an effective technique to improve the density of a saturated loose sand deposit.

2. Bat probe system description

The BAT probe system has been used for more than 25 years in groundwater and offshore investigations to collect fluid and gas samples, and to measure in-situ pore pressure, temperature, and the hydraulic conductivity of soils. This device was originally designed for sampling in-situ pore fluid but it was later modified to collect fluid/gas samples [10, 11]. This system is manufactured and sold by BAT Geosystems AB, Sweden.

The main components of the BAT probe are the BAT filter tip, the BAT/IS sensor, the battery unit, and the BAT/IS field unit. The filter tip is sealed at the top with a flexible septum that will automatically reseal after sampling. The septum can be penetrated with a needle several times without losing its self-sealing functions. The sensor is used for measuring/logging the pore pressure and temperature inside the filter tip. A hypodermic needle attached at the tip of the sensor is used to penetrate the filter tip. The battery unit is used to store the readings. The field unit is used to take real-time pressure and temperature readings and is also equipped with an internal atmospheric pressure sensor. Using the field unit, the sensor can be programmed to take readings at pre-established intervals. A detailed description of the device components, installation procedures and testing sequences are found in Christian and Cranston [11].

The in-situ testing technique presented herein was utilized to determine the type of gases released during blasting and their in-situ concentrations. However, this technique can be implemented to collect gases trapped in marine sediments, measure porewater, and temperature pressures at certain depths, detect shallow gas pockets during offshore oil or gas field developments, sample and identify contaminated soils, and to determine the coefficient of permeability of soil deposits.

2.1. Groundwater and gas sampling

Fig. 1 shows the BAT probe configuration when used for groundwater and gas sampling. The BAT probe is assembled as shown in Fig. 1b and carefully lowered down the 1-inch extension pipe. The double ended needle mounted in a quick coupling simultaneously penetrates the septum in the filter tip and the septum in the bottom of the container, allowing the in-situ liquid/gas to enter the container. Because the sensor is connected to the top of the container with a needle, it is also possible, using the field unit, to measure and monitor the pressure changes inside the container at any time during sampling. No change in pressure indicates that coupling was not achieved and sampling has not begun. Another advantage of this testing configuration is that pressurized samples can also be collected, if needed.

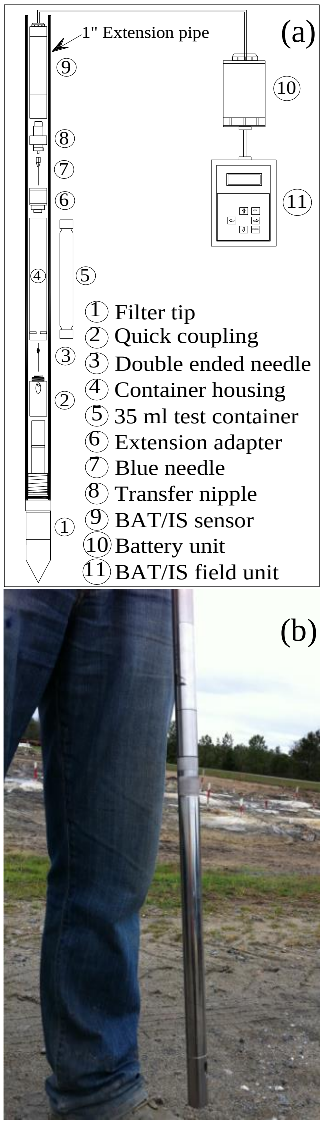

Figure 1. BAT system (a) schematic diagram and (b) assembled and ready for testing.

To collect in-situ groundwater/gas samples, the BAT probe system must be assembled as shown in Fig. 1b. Before placing the test container in the container housing, the air inside the container is removed by either applying vacuum to the container or by flushing and pre-charging the container with an inert gas that is not found in the ground. The time needed to collect a sample may vary from a couple of minutes to up to 24 hours or more depending on the soil type, sample collection technique and the difference in pressure between the inside of the container and the in-situ pore pressure. Pre-charging the container is desirable because it minimizes the uncertainties introduced by gases left inside the container when vacuum is applied [3].

3. Type and fate of gases produced during blast densification

The principal gases produced by typical explosives are water vapor (H_2O), carbon dioxide (CO_2), and nitrogen (N_2) in a mole ratio of 1:2:5 [12]. Hryciw [13] calculated that 1 kg (2.2 lb) of Ammonium Nitrate Fuel Oil (ANFO) will produce approximately 43 moles of these gases, which corresponds to about 1.0 m^3 (35 ft^3) of gas at standard temperature and pressure. However, after blasting some gas will escape to the surface, some will rapidly condense in the presence of cooling groundwater, and some will migrate and diffuse with time, making it difficult to predict a priori the exact amount of gas trapped in the soil.

Fig. 2 illustrates the fate of these gases following detonation of ANFO. From the released gases, nitrogen is the main gas that may remain trapped in the ground for a long period of time because the absolute pressure acting on this gas, at depths where blast densification is applicable, is relatively low and it does not dissolve easily in the pore fluid at these pressures (solubility coefficient, $\beta = 0.015$ mL of N_2/mL of water).

4. Influence of gas on soil response

Previous studies have shown that the mechanical behavior of soil is significantly affected by the presence of gas in either dissolved or free form. Grozic et al. [8] conducted a series of monotonic triaxial compression tests on loose specimens of gassy sand. They found that the stress-strain soil response is considerably affected by the amount of gas present in the soil mass. As shown in Fig. 3, the sample response changes from completely strain-softening to strain-hardening as the amount of gas increases, or the degree of saturation (S) of the sample decreases.

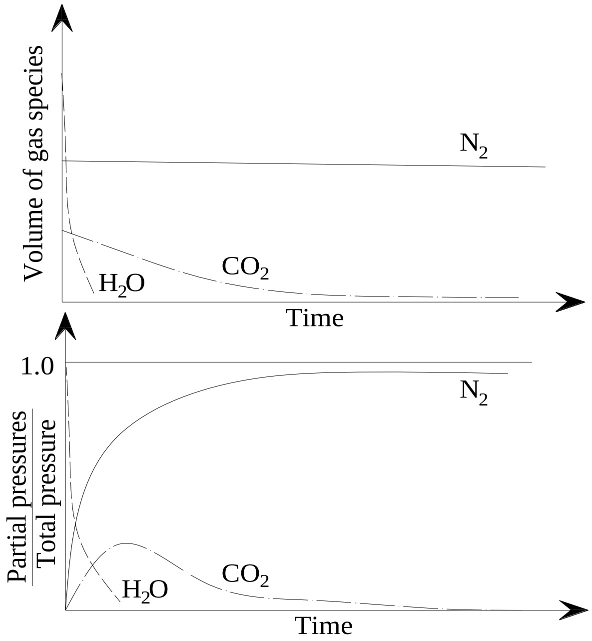

Figure 2. Fate of gases released by explosives.

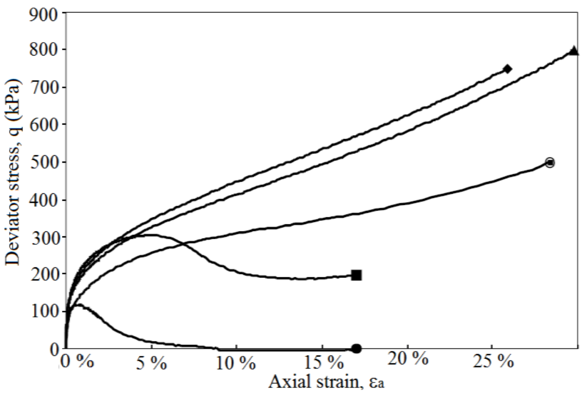

Figure 3. Stress-strain response for five representative loose gassy specimens. Source: (After Grozic et al. [8])

Rad et al. [7] showed that the shear strength of dense specimens of gassy sand is affected by the gas type, gas amount, and the pore pressure level. In contrast to the case of loose gassy sands, the presence of gas in free form has the effect of reducing the globally undrained shearing resistance of dense sands, because the increase in shear strength will be affected by the reduction in negative pore water pressure development.

Because nitrogen is a significant component of the explosion released-gasses and it may remain trapped in the soil for a long period of time, it is important to determine the type of gases released during blasting and their concentrations. These data are needed to evaluate, through laboratory testing, the behavior of blast-densified sands at a particular ground improvement project.

5. Field experimental program

5.1. Description of the site

As part of an ongoing blast densification program, two zones were blasted in 2011 at a waste disposal landfill in South Carolina, United States, to densify a loose sand deposit located between 7.5 and 12 m below the ground surface, and thus increase its resistance to liquefaction. Fig. 4 presents the results from the Cone Penetration Test (CPT) performed before blasting to determine the position of the loose sand layer.

In average, the depth to the top and thickness of the loose sand layer are 7.5 m and 4.0 m, respectively. Only the portions of the sand deposited in a very loose to loose state, N-values < 10 or $q_c/P_a < 4$ MPa [14], were considered to liquefy and contribute to ground surface settlements after blasting. The initial in-situ void ratio of the tested sand was $e_0=0.96$, and the minimum and maximum void ratios were determined as $e_{min} = 0.62$ and $e_{max} = 1.05$, respectively.

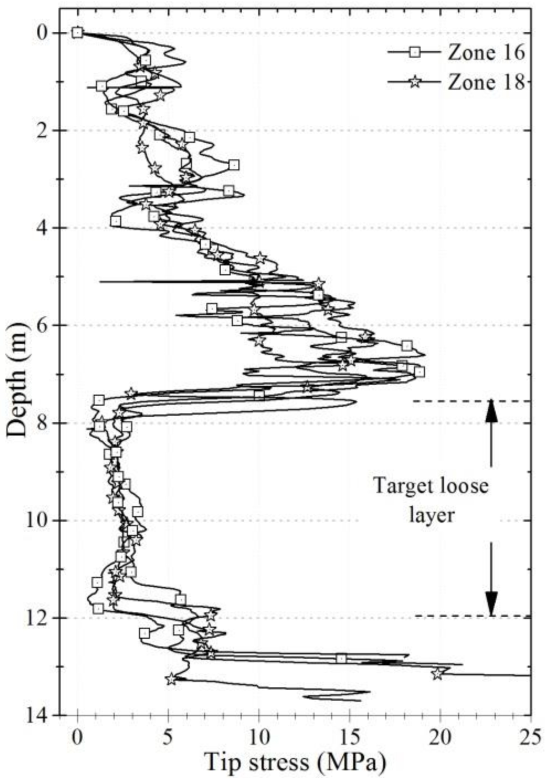

Figure 4. CPT results in zones 16 and 18 before blasting.

5.2. *Ground surface settlements*

Prior to ground improvement, standard topographic surveys along the centerline of each zone were conducted to establish the initial ground surface elevation condition. Ground surface elevations were also conducted after each blast event to measure the cumulative surface settlement at any stage during the blasting program. The monitoring of these surface settlements is essential to assess density changes as a result of blasting, and therefore to evaluate the effectiveness of the blasting program.

5.3. *Blast configuration and instrumentation*

As part of the field program, two areas termed zones 16 and 18 each measuring 30.5 m x 45.7 m were blasted. A total of six BAT probes were installed at a depth of approximately 10 m to collect groundwater and gas samples before and after blasting. Fig. 5 shows the blasting configuration, geometry and location of the BAT probes at these two zones. A total of four blast coverages were implemented at each zone to achieve the desirable ground surface settlement. The explosive charges were placed at a depth of approximately 10 m (middle of loose sand layer) and spaced in a square grid pattern with a fixed spacing of 6.1 m. The explosive used for this project was Hydromite 860, and a total weight of approximately 15.4 kg was placed in each blast hole. More details of the soil condition, soil properties, and blasting program at the site can be found in Vega-Posada [3] and GeoSyntec Consultant Inc. [15].

The BAT probes were installed four days after the second blast event, and the initial references values for the pore water pressure were measured two days after to ensure that the excess pore water pressure due to the second blast event and the installation of the BAT probes had dissipated at the time of the readings.

5.4. *Preparation and installation of the BAT probes*

The preparation and installation sequence of the BAT probes was as follows:

- A total of 40 ml, four times the volume the filter can hold, of de-aired water was flushed through the filter from the tip by using a syringe. After saturation, the filter was kept in a bucket under de-aired water to prevent desaturation.
- Using a Geoprobe 8040DT equipment, a drill pipe was pushed through the ground to approximately 1.5 m above the final depth of the filter tip. The drill pipe had a circular opening at the tip with a diameter of approximately 4 cm. An inner rod was placed inside the drill pipe to prevent soil from entering the drill pipe during pipe driving.
- After pushing the drill pipe to the desired depth, the inner rod was removed and the inside of the drill pipe was filled with water. The filter tip was screwed onto a 2.54 cm adapter pipe, while remaining submerged under de-aired water, and the first section of extension pipe was attached to the adapter pipe.
- Then, the bucket was quickly removed, the filter placed inside the drill pipe, and installation began. Extension pipes were used to reach the desired depth and a thread sealing agent was used at each connection to prevent leakage of water into the pipe.
- After lowering the filter tip through the drill pipe, it was pushed by the Geoprobe 8040DT approximately 1.5 m into the soil to reach the final depth.

and third set of samples were collected one day after the

5.5. *Container's preparation and testing*

Four sets of groundwater/gas samples were collected during this blast densification program. The first, second,

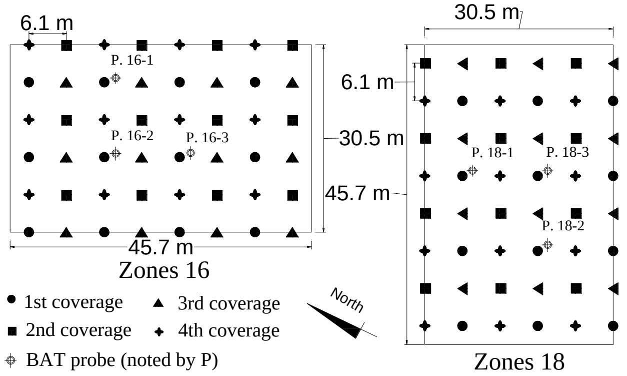

Figure 5. Blasting configuration and location of BAT probes in zones 16 and 18.

third blast event, immediately after the fourth blast event, and three days after the fourth blast event, respectively. For this set of samples, the BAT probe was assembled as shown in Fig. 1 and then a vacuum ranging from 85% to 90% was applied to the container from the bottom of the test container housing, to remove the air trapped in the container and in the sensor cavity.

The fourth and last set of samples was collected 27 days after the fourth blast event. For this set of samples, each container was flushed and pre-charged with Helium to minimize the uncertainties in in-situ gas concentration encountered when the vacuum method was used. The containers were pre-charged with a pressure slightly higher than the atmospheric pressure to ensure that contamination with atmospheric gases would not occur at any time during the sampling process.

Gas Chromatography (GC) tests were conducted on all the pre-charged containers before sampling to verify that no air was left inside. Helium was chosen to pre-charge the containers because it is an inert gas that is not readily found in the ground, it is not a gas produced by typical explosives, and it is different than the gas used as the carrier gas (argon) in the gas chromatography test.

6. Results of field investigation

6.1. Groundwater/gas samples

After collecting each set of samples, the containers were immediately sent to a commercial laboratory for GC tests to analyze the free gas in the headspace of the containers. The concentration of carbon dioxide (CO_2), carbon monoxide (CO), oxygen (O_2), nitrogen (N_2) and methane (CH_4) were determined.Tables 1 and 2 summarize the GC results from the vacuumed and pre-charged containers, respectively. For the pre-charged containers, the concentration of helium was not included in these tables since it was not part of the sampled gases. The concentrations of CO_2, N_2, and O_2 are expressed in percentage (%) and the concentrations of CO and CH_4 are expressed in ppmv (parts per million by volume). 1% by volume corresponds to 10,000 ppmv.

The concentration of nitrogen in the blasted layer ranged from 72.2% to 78.7% when vacuumed containers were used and from 5.0% to 8.5% when pre-charged containers were used. The concentration of gas obtained from these two techniques varied significantly. However, the results alone do not provide any valuable information about whether or not they are present in the ground in either dissolved or free form. The amount of gas that is being sampled is highly dependent on the difference in pressure between the container and the in-situ pressure, and on the volume of water that enters the container.

Rad and Lunne [10] proposed a set of equations to determine if the gases sampled with the BAT probe are present at the test location in dissolved and/or free form.

6.2. Porewater pressure measurements

The initial reference values for the in-situ pore pressures were recorded six days after the second blast event and one day before the third blast event. The excess pore water pressure due to the second blast event and the installation of the BAT probes had dissipated at the time of the readings. Table 3 summarizes the initial porewater pressure readings at all sample locations measured at a depth of 10 m. At these points, the temperature recorded was constant and equal to 20.1 ºC.

Table 1.
Results from GC tests - vacuumed containers.

Borehole #	First set of samples					Second set of samples					Third set of samples				
	CO_2	N_2	O_2	CO	CH_4	CO_2	N_2	O_2	CO	CH_4	CO_2	N_2	O_2	CO	CH_4
	(%)	(%)	(%)	(ppmv)	(ppmv)	(%)	(%)	(%)	(ppmv)	(ppmv)	(%)	(%)	(%)	(ppmv)	(ppmv)
P. 16-1	1.8	75.2	19.7	6	41	3.3	73.8	18.7	24	39	-	-	-	-	-
P. 16-2	1.4	77.1	13.8	>2250	3680	2.2	73.2	17.5	4400	3300	2.4	76.0	14.8	4800	3700
P. 16-3	1.4	77.6	18.5	34	208	2.8	72.8	19.7	57	300	2.3	73.2	21.4	10	244
P. 18-1	2.4	78.7	15.9	15	75	3.3	76.5	16	20	124	2.8	72.4	20.6	10	90
P. 18-2	1.5	76.9	17.8	231	140	2.5	75.2	18.5	51	123	2.4	72.2	20.8	14	144
P. 18-3	2.2	77.6	16.4	12	12	3.2	77.0	15.8	24	12	2.0	74.3	19	9	13

Table 2.
Results from GC tests - precharged containers.

Borehole #	Sample 1				Sample 2				Sample 3			
	CO_2	N_2	CO	CH_4	CO_2	N_2	CO	CH_4	CO_2	N_2	CO	CH_4
	(%)	(%)	(ppmv)	(ppmv)	(%)	(%)	(ppmv)	(ppmv)	(%)	(%)	(ppmv)	(ppmv)
P. 16-3	0.6	8.5	1	89	0.3	6.7	1.2	51	0.4	6.8	<1	83
P. 18-1	0.4	6.1	1.5	11	0.2	6.2	1.7	10	0.3	6.9	1.6	20
P. 18-2	0.3	6.3	1.2	13	0.3	6.2	1.0	22	0.3	6.4	1.1	26
P. 18-3	0.4	7.4	1.7	<1	0.2	5.0	1.3	<1	0.3	5.9	1.4	1.0

Table 3.
Initial in-situ pore pressure after installation of the BAT probes (depth = 10 m).

Borehole (#)	Pore Pressure (kPa)	Average pore pressure (kPa)
P. 16-1	95.4	
P. 16-2	97.5	95.8
P. 16-3	94.4	
P. 18-1	92.0	
P. 18-2	91.0	92.1
P. 18-3	93.4	

The BAT probe system was used to measure the excess pore pressure dissipation over time. Fig. 6a and 6b show the pore pressure dissipation after the third and fourth blast events measured at boreholes P.16-3 and P.18-3, respectively. The pore water pressure was equivalent to the in-situ total vertical stress, indicating that initial liquefaction was induced in these zones after blasting. The effective in-situ vertical stress in these two zones was approximately 100 kPa. The excess pore pressure decreased to the pre-blasting value in approximately 70 hr and the majority of the blast-induced settlements is expected to occur during this period of time [16].

6.3. Ground surface settlements

Fig. 7 shows the cumulative axial strains after each blast event in zones 16 and 18. The total settlement measured at the ground surface is expected to occur within the blasted loose layer [16, 17], and the ground surface to experience an one-dimensional consolidation response ($\varepsilon_v \cong \varepsilon_a$) [18].

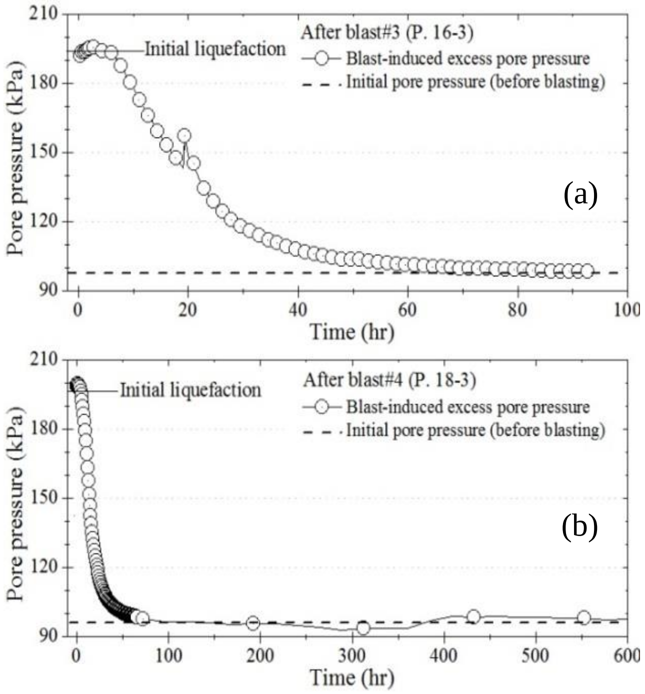

Figure 6. Pore pressure dissipation over time after blasting measured at (a) zone 16 and (b) zone 18.

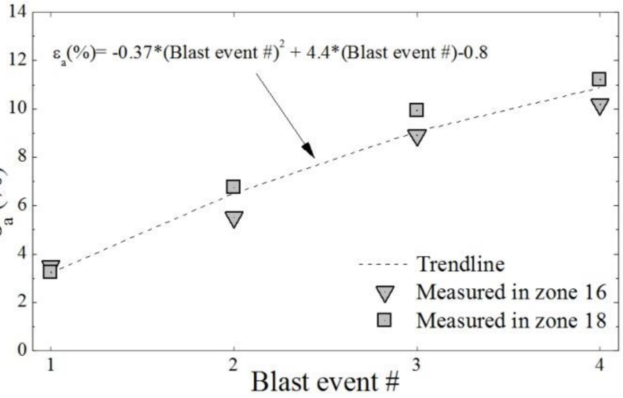

Figure 7. Cumulative axial strains in zones 16 and 18.

The axial strain measured in the targeted layer was 3.2%, 6.5%, 9.1% and 10.8% after the first, second, third, and fourth blast event, respectively. The decreased in void ratio after the fourth blast event was 0.22 ($\Delta e = \varepsilon_v (1+e_0)$), and the resultant void ratio was 0.74. This void ratio corresponds to a relative density of 72%, where a dilative response is expected when subjected to axial compressive loading (i.e., embankment) and hence, after densification, the soil is not considered susceptible to liquefaction and flow.

7. Summary and conclusions

The BAT probe testing technique was successfully implemented to collect groundwater and gas samples and to measure the porewater pressures response during and after blasting.

From the groundwater/gas samples collected in the densified zones and considering that the porewater pressure at the depth of sampling is low, nitrogen is most likely to be the only gas remaining in the ground in the form of free gas. The percentage of nitrogen detected in the BAT containers' headspace ranged from 72.2% to 78.7% and 5.0% to 8.5% when vacuumed and pre-charged containers were used, respectively.

The porewater pressure recorded after detonation showed that liquefaction was induced in the tested zones. The sand remained liquefied for a period of approximately 6 hours and the excess pore pressure decreased to the pre-blasting value in approximately 70 hr.

The results obtained from the topographic surveys proved that the blast densification technique is an effective technique to improve the density of the sand deposit. A total axial strain of 10.8 % was achieved in the targeted layer after the fourth and last blast event.

Acknowledgments

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