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> WHITE PAPER #05

Pneumatic Fracturing

Applying pneumatic fracturing beneath industrial structures for in situ remediation

Abstract:

This paper describes the results of an instrumented field test and structural analysis of a steel frame industrial building [picture right] subjected to differential ground surface heaving caused by pneumatic fracturing. Pneumatic fracturing is a patented site remediation technology that involves injections of controlled pressure air into geologic formations which can cause the ground to heave upward. At this test site pneumatic fracturing was integrated with in situ dual phase extraction to remove volatile organic compounds from both the vadose and saturated zones. Over a two year period trichloroethylene concentrations in source monitoring wells were reduced from a high of 62,000 micrograms per liter to an average low of approximately 1215 micrograms per liter. Fracturing was conducted within

the industrial building at depths ranging from 3.5 m (11.5 ft) to 7.3 m (24.0 ft) below grade. Building movements and deformations were monitored using four independent instrumentation systems consisting of electronic strain gages, electronic linear variable differential transducers, electronic tiltmeters, and optical engineering levels. A temporal analysis of the strain and deformation data revealed that maximum stresses in the steel members during injection ranged up to 22.9 percent of the original design stress, while residual stresses were less. These test results indicated that the structural integrity of the building was not seriously affected by the fracturing operations. A procedure is presented for evaluating the feasibility of performing pneumatic fracturing beneath or adjacent to structures and utilities.

INTRODUCTION AND TECHNOLOGY BACKGROUND

The effectiveness of most in situ remediation technologies at contaminated sites depends to a large extent on the characteristics of the geologic formation. The factor which most often restricts the successful application of in situ remediation is low hydraulic conductivity (i.e., <math><10^{-4}</math> cm/sec). To overcome this limitation a patented process called "pneumatic fracturing" was developed at the Hazardous Substance Management Research Center at the New Jersey Institute of Technology in Newark, New Jersey (U.S. Patent No. 5,032,042). The process creates a radial fracture network that emanates outward by injecting high pressure air into a discrete zone within a vertical well. The fracturing process locally increases formation permeability and reduces heterogeneities, thereby improving access to the contaminants which in turn can either be removed and treated above-ground, or treated in place using in situ remediation techniques. The overall objective of pneumatic fracturing is to increase treatment rates and reduce treatment times.



fracturing process has been used as an injection tool to deliver a wide range of materials (e.g., dry powder, liquid, or slurry) into the fracture network to further enhance remediation processes. The remediation technologies which pneumatic fracturing has been integrated with include vapor extraction, pump and treat, dual phase extraction, free product recovery, air sparging, bioaugmentation, biostimulation, in situ vitrification, and reactive media injection (e.g., zero-valent iron). Pneumatic fracturing is currently offered commercially and has been successfully applied at over 50 sites under a variety of geologic conditions.

During the pneumatic injection process, the geologic formation in the vicinity of the fracture plane will deform vertically as the fracture propagates horizontally. For shallow to intermediate fracture injection depths, i.e., <math><9\pm</math> m (30± ft), these deformations can translate into measurable heaving of the ground surface. The magnitude and extent of the surface heave depends on a number of factors including the injection

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In addition to permeability enhancement, the pneumatic

pressure/flow rate, injection depth, formation geology, and the stiffness of overlying structures/pavements. Maximum ground surface heave is typically observed at the injection point, and tapers to zero with increasing radius. Peak heave values are transient, occurring only during the pneumatic injection (about 20 seconds) and have ranged from less than 2.5 mm (0.1 in.) to more than 25.4 mm (1.0 in.) observed at the injection point. Residual heaves (i.e., after completion of fracturing) are significantly less with maximum values of less than 6.4 mm (0.25 in.).

At industrial sites, soil and ground water contamination are common occurrences beneath or adjacent to structures and utilities, principally because these facilities were often the source of the contamination. If such facilities are to remain active, in situ remediation technologies such as pneumatic fracturing offer the only alternatives for clean-up. The economic incentives at such sites are substantial since it avoids facility relocation and the associated temporary loss of service.

It is estimated that more than 50 percent of pneumatic fracturing projects have involved integrity questions with structures or utilities. Therefore, control of subsurface pneumatic injections to limit ground heave within a range which can be tolerated by the structure is essential to extend the technology to commonly encountered site conditions. Analysis of the interaction between heaving geologic formations and surface structures is complex due to the variety of building types that exist at contaminated sites, as well as the varying elastic properties of geologic formations. The major goal of this study was to conduct a coordinated field test and structural analysis of an actual industrial structure subjected to pneumatic fracturing. The paper begins with a discussion of tolerable differential movements for structures and utilities found at industrial facilities. Next, the test set-up and results of an actual field test involving pneumatic fracturing beneath an industrial facility are presented. The paper concludes with a suggested procedure for evaluating the feasibility of conducting pneumatic fracturing beneath structures and utilities.

TOLERABLE DIFFERENTIAL MOVEMENTS

The magnitude and shape of ground deformations caused by pneumatic fracturing, as well as the manner in which they affect structures and utilities, are similar to those observed in other areas of civil engineering practice. It is widely acknowledged that most structures experience some amount of movement during their service life, usually in the form of downward settlement due to soil compression, and cyclical heaving and settling due to seasonal variations of soil moisture and temperature. In most cases, these movements are small and do not adversely affect the serviceability of a particular structure unless the magnitudes are significant.

It is difficult to determine the exact magnitude of differential foundation movement that will initially cause cosmetic (i.e., architectural) damage to structures, or more seriously, structural damage. Empirical guidelines for tolerable movements have been established based on observations of actual building movements and the resulting damages, e.g., Skempton and MacDonald (1956); Polshin and Tokar (1957); Sowers (1962); Bjerrum (1963); Grant, Christian, and Vanmarcke (1974); Burland and Wroth (1974); and Myslivec and Kysela (1978). Most of these investigators provide criteria for tolerable ground/structure movements to avoid cosmetic damage.

Burland and Wroth (1974), in a state-of-the-art report, investigated settlement and distortion criteria for load-bearing walls undergoing "hogging." Hogging is defined as upward concave heaving as occurs on expansive soils or downward concave differential settlement which can result from inadequately braced excavations adjacent to structures. Burland and Wroth concluded that the tolerable deflection limits for hogging were half the tolerable limits proposed by other investigators. Since the form of ground deformation resulting from pneumatic fracturing is frequently similar to a structure undergoing hogging, these criteria can be useful for evaluating pneumatic fracturing projects. Some tolerable differential movement guidelines for industrial structures undergoing hogging which have

been adapted from the literature are presented in Table 1.

TYPE OF STRUCTURE	DEFLECTION RATIO, D / L
Unreinforced Masonry Walls	0.0005
Rigid Reinforced Concrete Structures	0.0015
Rigid Steel Framed Structures	0.0010
Semi-Flexible Steel Framed Structures	0.0025
Traditional Frame Buildings	0.0020
Plaster/Gypsum Walls (point at which they start cracking)	0.0010

NOTES:

L = distance between adjacent columns that heave differently, or between any two points that heave different amounts.

H = height of the structure.

D = relative deflection, or heave of a point relative to a straight line connecting two reference points at a distance, L, apart. A negative D indicates a situation known as hogging and a positive D indicates a situation known as sagging.

D / L = deflection ratio, also known as the hogging ratio or the sagging ratio.

Table 1. Tolerable Differential Movements for Structures Undergoing Hogging (adapted from Burland and Wroth, 1974; Skempton and MacDonald, 1956; Polshin and Tokar, 1957; and Sowers, 1962).

Foundation movements can also cause structural damage to buildings, although such damage is less common and will occur at larger deflection ratios than those cited above. A discussion of the more common structural distress situations related to foundation movements are presented in Schuring, Raghu, and Dauheimer (1988). These situations include: (1) the loss of beam bearing, (2) tilting and/or buckling of walls, and (3) development of secondary stresses in members. It must be emphasized that each distress situation is unique due to varying materials, construction types, and structure conditions; therefore, each site should be evaluated by a competent engineering professional.

Available studies on allowable movement for utility piping are more limited. The ability of a buried utility to sustain differential movements depends on the piping material, condition of the pipe, and the way in which it is installed. In general, utility piping materials can be divided into three major classifications: rigid (e.g., cast iron, concrete), semi-rigid (e.g., steel), and flexible pipes (e.g., copper, PVC, fiberglass). A practical way of evaluating allowable movements for pipe materials is to use the concept of deflection limit, d / L , which is defined as the maximum amount of transverse deflection per

unit length that a pipe can tolerate before permanent deformation takes place. For example, steel pipe, which is considered semi-rigid, is generally designed with a maximum deflection limit of 7.5 percent, which reportedly already contains a factor of safety of four (American Institute of Steel Construction, 1984). Flexible pipes such as certain plastics and fiberglass are typically designed for deflection limits of 5 percent or more, which also contains a factor of safety of about four. Rigid materials such as cast iron and concrete pipes can only tolerate small deflections (e.g., < 0.5 percent) before cracking or brittle failure (American Concrete Pipe Association, 1980). In general, the newer the utility, the less likely it will be affected due to increased material flexibility and improved bedding practices.

The nature of the product being carried within the pipe is probably the most important factor in determining allowable movement criteria for utility pipes. The consequence of failure for certain utilities can be costly, and may even be dangerous. Therefore, when fracturing is conducted in the vicinity of critical utilities such as natural gas, chemical lines, and fuel supplies, the integrity of the pipes should be monitored. Other utilities such as storm sewer, water, and sanitary sewer lines usually pose less of a risk if damaged.

INDUSTRIAL SITE BACKGROUND

The instrumented field test to investigate the effect of pneumatic fracturing injections on overlying structures was performed on a vacant manufacturing and warehouse facility located in Middlesex County, New Jersey. Operation of the facility ceased a number of years ago and the only site activity occurring during the course of this study was an active subsurface remediation. A brief description of the site history, hydrogeology, and remediation status are presented below.

Site investigations performed over the last decade revealed that volatile organic compounds (VOCs) were present in both the vadose and saturated zones, and that the contamination had spread over an area of approximately one acre. The VOCs detected included trichloroethylene (TCE) and its biodegradative break-

down products such as cis-1,2 dichloroethylene (cis-1,2-DCE) and vinyl chloride (VC). Additionally, significant quantities of toluene were detected in one monitoring well.

The site was underlain by the New Jersey Passaic (Brunswick) Formation which consists of a monotonous succession of redbeds deposited during the Triassic Period. The dominant lithology is mudstone with occasional interbeds of shale and sandstone. The upper zone of the rock is typically weathered and fractured to depths ranging from approximately 3 m (10 ft) to 6 m (20 ft). In spite of the natural fractures, the Passaic Formation characteristically has a moderate to low permeability. The ground water table varied across the site from 2.1 m (7 ft) to 3.4 m (11 ft).

Chlorinated organic compounds in the Passaic are a widespread problem since the formation underlies approximately 25 percent of the State of New Jersey which also corresponds to the state's main industrial belt. A condition frequently encountered is migration of contaminants through the weathered rock zone and into the more competent bedrock below.

In 1991 a dual vacuum extraction pilot test was performed in the suspected source area. The goal was to extract VOCs from the formation in both the vapor phase and dissolved phase utilizing a high vacuum system. To further enhance contaminant removal, air was injected through bedrock piezometers installed at various depths. The results of the pilot test confirmed that the subsurface permeability was quite low. The vacuum radius of influence ranged between 2.1 m (7 ft) and 4.6 m (15 ft), and a 24 hour pump test showed less than 0.2 m (0.6 ft) of drawdown within a 12.2 m (40-ft) radius. Based on the results of these tests, remediation time was projected to be up to a decade or more, and required the installation of more than 75 treatment wells. In view of the unpromising pilot test results, the site owner decided to seek an alternative remediation solution.

In 1994, ARS Technologies, Inc. (formerly Accutech Remedial Systems) was engaged to develop an

alternative plan for remediation of the site. They decided to apply the Pneumatic Fracturing Extraction (PFESM) process at the site to increase formation permeability and improve access to the VOC plume. Through the use of fracturing, the design spacing of the treatment wells was increased to an average of 9.1 m (30 ft) in both the strike and dip directions, resulting in significant capital cost savings. In 1995, ARS Technologies, Inc. commenced operation of a dual extraction system involving simultaneous removal of contaminated soil vapor and ground water with above-ground stripping and treatment. A total of 15 multiple purpose wells were installed which were initially pneumatically fractured, and then converted into dual extraction wells. Based on design analyses, it was estimated that clean-up goals would be reached by operating the dual extraction system for two years, followed by an additional two years of just pump and treat.

At the end of 1996 source zone ground water concentration levels of TCE of 1 to 5 parts per million were obtained with no adverse "rebound" effects, indicating that target clean-up concentrations at the study site were approaching risk-based cleanup levels after just two years of dual phase extraction system operation.

Table 2 contains a summary of ground water sampling results showing the reduction in VOC concentrations for monitoring wells in the source area. The site owner and consultant are now in the process of applying for "no further action" under the New Jersey Department of Environmental Protection (NJDEP) regulations to close the site. If granted, the clean-up will have been accomplished in less than half the remediation time originally estimated by ARS Technologies, Inc., and far less than the original estimate of a decade or more.

Monitoring Well	May 1990		December 1994		December 1996		January 1997	
	TCE	cis-1,2-DCE	TCE	cis-1,2-DCE	TCE	cis-1,2-DCE	TCE	cis-1,2-DCE
MW-2	160,000	6,600	62,000	13,000	420	21	1,500	120
MW-3S	8,300	1,400	17,000	1,800	980	140	2,630	150
MW-6	7,100	2,200	39,000	12,000	250	120	1,150	77
MW-12	3,000	170	5,100	400	1,100	92	145	9
MW-13	100,000	16,000	9,900	2,300	440	52	650	120

NOTE: All concentrations are in micrograms/liter (µg/L).

Table 2. VOC Concentrations in Ground Water Samples from Selected Monitoring Wells, Middlesex County, New Jersey.

FIELD TEST SET-UP

The field test structure was a one-story, steel frame building with brick masonry shear walls and a concrete slab-on-grade. A total of five separate pneumatic injections were made at different depths below the structure ranging from 3.5 m (11.5 ft) to 7.3 m (24.0 ft). A typical fracture injection sequence for this study involved the following steps: (1) a high flow (HQ) injector was placed into the borehole at the depth interval to be fractured; (2) a 0.8-m (2.5-ft) interval was sealed off by inflating the flexible packers on either side of the HQ injector; (3) the monitoring instruments were activated to begin sampling; (4) a surge of pressurized air from the tanks was applied to the packed-off interval at a predetermined setting for approximately 15 seconds; and (5) the packers were depressurized, the HQ injector was moved to the next depth, and the process was repeated. The entire cycle for each injection was approximately 30 minutes in duration, which included downloading data and resetting the monitoring instruments. It is noted that the structural analysis in this study focused on the shallowest injection, i.e., 3.5 m (11.5 ft) to 4.3 m (14 ft). The other fracture injections were at deeper intervals and provided similar results, but as expected, caused smaller structural movements.

Building movements and deformations were monitored using four independent instrumentation systems consisting of bonded foil resistance strain gages, linear variable differential transducers, biaxial tiltmeters, and optical engineering levels with graduated heave rods. The electronic instrumentation provided a dynamic time-history of the building movements and stresses in the structural members.

Eighteen (nine pairs) electronic strain gages were used to measure the stress levels in the steel members during injection and to provide qualitative visualization of the overall structural deformation. Strain gages were bonded to the flanges of the steel columns and beams at

distances from the injection well of up to approximately 13.2 m (43.4 ft). Twelve highly sensitive electronic biaxial tiltmeters were used to measure the angular deflection of the concrete slab-on-grade around the fracture well during the fracturing event. Tiltmeter sensors were positioned 2.4 m (8 ft), 4.9 m (16 ft), and 7.6 m (25 ft) from the injection point in the four orthogonal directions. Five linear variable differential transducers (LVDTs) were used to calibrate the tiltmeter data by providing the actual vertical displacement of the concrete slab-on-grade during the injections. The LVDTs were installed in a radiating pattern around the fracture well at distances ranging from 1.2 m (4 ft) to 4.0 m (13 ft). Data from the strain gages, tiltmeters, and LVDTs were recorded for a 3 to 5 minute period at a sampling rate of 2 times per second using a microcomputer-controlled data acquisition system.

In addition to the electronic instrumentation, six optical engineering levels with graduated heave rods were used to monitor the concrete slab and column movements. These data were used to complement data from the strain gages and the LVDTs. Four levels were targeted at the bases of structural steel columns, one was sighted next to the injection well, and the last was sighted on a structural masonry wall.

FIELD TEST RESULTS AND ANALYSIS

Analysis of the instrumentation data showed that the maximum observed ground surface heave during pneumatic injections ranged up to 15.9 mm (0.625 in.), and the maximum observed relative rotation of the structure was approximately 0.07 degrees. The surface area influenced by the fracturing was nearly circular and had an average radius of 10.7 m (35 ft). Maximum residual heave after completing the pneumatic fracturing injections was 3.2 mm (0.125 in.).

A structural analysis of the key steel members of the building frame was performed to compare the stresses induced by the fracture injections with the original design stresses for the building. Data from the strain gage pairs were inspected to determine the type of bending occurring at each location, and column base

rotations were approximated using the tiltmeter data. This allowed a determination of the general deflected shape of the structure during maximum ground heave. For purposes of the analysis, dead loads were based on measurements of the actual building materials, and live loads were estimated using code design values in effect at the time of the original construction.

The results of the structural analysis revealed that all stresses experienced during the pneumatic injections were well within the design factor of safety and elastic range of the structural steel. Maximum stresses in the steel members ranged up to 22.9 percent of the estimated original design stress, while residual stresses were consistently less, ranging up to 11.1 percent. It was concluded that the overall structural integrity of the warehouse building was not adversely affected.

Although the warehouse did not have any interior finishes, the potential for cosmetic damage was evaluated. The maximum deflection ratio, D/L , measured between individual column footings was approximately 0.0012. The maximum deflection ratio with respect to the concrete slab-on-grade was approximately 0.0005. A comparison of these ratios with the movement criteria presented in Table 1 suggests that had the test structure contained any interior finishes (e.g., plaster walls), there would have been some cosmetic damage.

A temporal analysis showed progressive structural movements and stress reversals in the framing members which suggests the potential for different types of damage at different times during an injection event. The data also revealed that the steel structure and the floor slab acted as independent units, with the columns showing larger magnitudes of heave than the slab at the same location. This is illustrated in Figure 1 which shows both the maximum and residual heave value measurements. This was attributed to the column footings being located several feet closer to the actual pneumatic injections. It is noted that the vertical scale of Figure 1 has been greatly exaggerated with respect to the horizontal scale for the purpose of visualization.

Figure 1. Sections Showing Maximum and Residual

Heaves for the Slab-on-Grade and the Columns.

PROCEDURE FOR EVALUATING STRUCTURES

This section outlines a procedure for evaluating the feasibility of performing pneumatic fracturing beneath or adjacent to structures and utilities. It is based on the results of the current study, as well as past experience with fracturing. It is only a guideline, and sound engineering judgment must be applied depending on site specifics. The procedural steps are as follows (Schuring, et. al., 1996).

STEP 1 - Investigate the Facility Function: Define the function of the facility, and determine how critical are its operations. Of special interest are industrial processes with hazardous materials and sensitive machinery which cannot tolerate movement.

STEP 2 - Review As-Built Information (including utilities): As-built drawings and other information should be consulted to establish the dimensions and composition of the structure and utilities. If as-builts are not available, exploratory test pits and cores may be necessary to determine actual dimensions of foundations and slabs. It is important to thoroughly investigate all utilities in the area, especially critical utilities such as natural gas, liquid fuels, and hazardous chemicals.

STEP 3 - Conduct and Document a Condition Survey: A walk-through of the facility should be conducted and the condition of the structure examined. Any existing cracks or other distress should be documented with photos, a video, or both. Strain telltales should be installed across selected joints and significant existing cracks.

STEP 4 - Establish Allowable Movement Criteria: Based upon information gathered in the previous steps, allowable movement criteria can be established using the values presented previously in Table 1. This should be coordinated with the facility's structural engineer.

STEP 5 - Perform Fracture Injection Design: The most cost effective approach for minimizing potential effects of fracturing is to locate the injection wells a safe distance from footings and utilities. Design calculations

should be performed to check the effect of heave on the structure using a suitable method (e.g., elastic plate bending theory). Calculated heave values should be compared with allowable movement criteria, and fracture pressures and flow rates should be adjusted accordingly. If reliable soils data are not available, testing of recovered samples should be performed and evaluated by a geotechnical engineer.

STEP 6 - Pilot Test: If the results of the injection design analysis (i.e., Step 5) indicate that fracturing can be conducted safely, a field pilot test is recommended. The pilot test can be conducted outside the structure to assess the elastic properties of the geologic formation, or alternatively can be performed within the structure by gradually stepping up injection pressures and flow rates. Movement monitoring instrumentation (e.g., optical levels, tiltmeters, strain gages, and LVDTs) should be employed during the pilot test as appropriate.

Experiences from this field test and more than 40 previous pneumatic fracture sites were used to develop a ground deformation model based on the theory of elastic plate bending (Canino, 1997). The model is now being expanded to include an overlying structure which is treated as an additional elastic layer with a stiffness which varies according to the rigidity of the building.

CONCLUSIONS AND RECOMMENDATIONS

This study has presented a brief discussion of the pneumatic fracturing process and its potential effects on overlying structures. Differential movement criteria for various classes of structures and utilities has been reviewed. An instrumented field test of pneumatic fracturing beneath an industrial structure has been described which allowed measurement of the dynamic response of this structure to differential ground movements. Test results showed that the overall integrity of the structure was not seriously affected, although the movements were of sufficient magnitude to cause cosmetic damage. The paper concludes with an outline of a procedure for evaluating structures subjected to pneumatic fracturing. Although the results of this field

test provided valuable insight into the behavior of structures subjected to pneumatic fracturing, more data are needed from fracturing in different formation types beneath various types of structures.

ACKNOWLEDGMENTS

The authors wish to acknowledge Professor Edward Dauenheimer, New Jersey Institute of Technology, Newark, New Jersey, USA, for his assistance with the field study presented. His expert technical consultation on instrumentation and structure behavior are sincerely appreciated.

The authors would also like to thank the Hazardous Substance Management Research Center at the New Jersey Institute of Technology, Newark, New Jersey, USA (a National Science Foundation Industry / University Cooperative Research Center); ARS Technologies, Inc. (formerly Accutech Remedial Systems); and the Civil and Environmental Engineering Department of the New Jersey Institute of Technology, Newark, New Jersey, USA, which made this research possible.

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