Assessing Environmental Impacts of Horizontal Gas Well Drilling Operations

AGM 064

Project Overview:

Water and Waste Stream Study

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Pits and Impoundments Study

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List of Abbreviations

ASTM	American Society for Testing and Materials
Ba	Barium
BOPs	Blowout preventers
Br	Bromide
CEE	Civil and Environmental Engineering
Cl	Chloride
DO	Dissolved oxygen
DRO	Diesel range organics
EAP	Emergency Action Plan
FB	Flowback
ft	Feet
GPS	Global Positioning System
HF	Hydraulic fracturing, fracking or frac
HFF	Hydraulic fracturing fluids
I	Inorganic (parameters)
MBAS	Methylene blue active substances (surfactants)
MCL	Maximum contaminant level
mrem/hr	Millirems per hour (rem = roentgen equivalent man)
MU	Makeup
ND	Not determined (also shown as N/A)
O	Organic (parameters)
PID	Photo-ionization detector
R	Radioactive (parameters)
SDWA	Safe Drinking Water Act

TDS	Total dissolved solids
TPH	Total petroleum hydrocarbons
VOC	Volatile organic compound
WVCSR	West Virginia Code of State Regulations
WVDEP	West Virginia Department of Environmental Protection
WVU	West Virginia University
WVWRI	West Virginia Water Research Institute

Project Overview

Although hydraulic fracturing is not a new technique, its rapid development in the Marcellus Shale Formation has caused concern regarding the potential risks to human health and the environment. On December 14, 2011, the West Virginia Legislature (Code of State Regulations §22-6A) enacted the Natural Gas Horizontal Well Control Act. The act directs the West Virginia Department of Environmental Protection (WVDEP) to conduct several studies in order to collect information and report back its findings and recommendations. In summary the act focuses on:

- Light, noise, dust and volatile organic compounds air emissions as they relate to the well location restrictions regarding occupied dwelling structures
- Impoundment and pit safety
- Possible health impacts from water, waste and air emissions related to horizontal drilling and completion activities

In support of these legislative mandates, the WVDEP solicited a team of researchers from WVU to conduct these studies. Led by the West Virginia Water Research Institute (WVWRI), the WVU researchers studied the potential for horizontal gas well development to affect air and water quality. Effects of light and noise, and the structural integrity and safety of wastewater pits and impoundments were also studied. Literature reviews were conducted and followed by direct field monitoring of air, noise and light and well development water and waste streams. This overview document focuses on the activities undertaken to characterize the process waste streams as well as the pits and impoundments safety study.

This overview deals with impoundment and pit safety, including an evaluation of process waste streams associated with horizontal well drilling. The study does not address the potential for human exposure via fluid movement from the fracturing zone upwards toward drinking water supplies. The air emissions, light and noise report will be the subject of a future submittal from WVU.

Water and Waste Stream Study

An extensive literature review was conducted to characterize the water and waste streams associated with the development of horizontal shale gas wells including commonly used hydraulic fracturing fluids. Specific areas of review included: public health, environmental, and safety aspects of hydraulic fracturing development. The review also included surface and groundwater contamination and well development practices commonly used to protect surface and groundwater during well development. The literature review was used in developing an on-site water and waste stream monitoring plan by defining sample parameters and procedures. The water and waste stream monitoring plan was updated as active well sites were monitored and study design and sampling methods were adjusted to field conditions.

This field study focused on sampling and chemical analysis of drilling fluids, muds and cuttings along with hydraulic fracturing fluids and flowback waters of working hydraulic fracturing sites in the Marcellus Formation in West Virginia. The list of analytical parameters used in this study was developed through literature review and finalized in conjunction with the staff of WVDEP. The list includes both primary and secondary drinking water contaminants. Contaminants were evaluated based on exceedance of maximum contaminant levels as identified under the Safe Drinking Water Act (SDWA).

West Virginia recently began permitting the construction of centralized pits for the storage of flowback water. Groundwater monitoring is required for centralized pits in West Virginia and groundwater monitoring wells are installed by the permit holder. As of the date of this report, only one permit had been issued for centralized waste storage pits. This site was selected for groundwater monitoring and was one of several sites used for flowback characterization. The centralized impoundments initially stored makeup water (a combination of Ohio River water and treated mine water). After hydraulic fracturing, the impoundments were converted to flowback water storage. Water in the impoundments was analyzed before and after conversion to flowback storage. Monitoring wells were sampled to identify any groundwater contaminants before and after placement of flowback in the impoundments.

Site Sampling

The nomenclature for hydraulic fracturing wastewaters is not standardized across the industry. For the purposes of this study *hydraulic fracturing fluids* refer to the fluids injected with proppant in order to generate sufficient pressure to create fractures within the targeted formation. The term *flowback* refers to all fluids that return to the wellhead after hydraulic fracturing and prior to gas production. This includes hydraulic fracturing fluids, gases, gas liquids and water. *Produced water* consists of fluids that return to the wellhead subsequent to gas production. In addition, reference to *brines* within this report refers to flowback waters with total dissolved solids (TDS) values greater than 35,000 mg/L. As the well is drilled, *muds* are used to cool the drill bit, control well pressures and lift rock *cuttings* to the surface. *Cuttings* and *muds* are separated at the surface where *muds* are typically recycled. Spent drilling *muds* and *cuttings* are removed for disposal.

Active hydraulic fracturing wells in northern West Virginia were sampled to determine contaminant concentrations in:

- Hydraulic fracturing fluids
- Flowback
- Drilling muds and cuttings

- Groundwater monitoring wells

WVDEP contacted natural gas developers and established access to Marcellus gas well sites for WVU researchers to collect water and waste stream samples. Liquid and solids samples were collected and analyzed for a wide range of inorganic, organic and radioactive constituents to characterize the water and waste streams associated with the various stages of horizontal gas well development. While in the field, WVU researchers noted current weather conditions and sampling time. They conducted a general radiation sweep of the sampling area and individual samples with a handheld radiation alert detector that displayed current radiation levels in millirem per hour (mrem/hr) and scanned for off-gases of volatile organic compounds (VOCs) with a photo-ionization detector (PID) as part of personal safety procedures. Parameters such as pH, specific conductivity, TDS, dissolved oxygen (DO), salinity and temperature of samples were measured in the field using a multi-parameter YSI56 unit. At least one site, for each stage of horizontal gas well development, was sampled.

To ensure completeness and consistency in sampling, a site checklist was developed. The checklist covers information relevant to the site location, stage of well development, samples collected and field observations. Samples were sent to certified laboratories, REI Consultants for organic and inorganic compound determinations and Pace Analytical for radioactivity analysis. It is important to note that all chemical determinations are for total as opposed to dissolved concentrations. It is important to note that one of the organic parameters: Total petroleum hydrocarbons (TPH) (diesel range) measure all hydrocarbons in the range of C11 to C28. That range includes not only diesel fuel but the plant products: vegetable oil and guar gum. The latter is a common additive in hydraulic fracturing fluids. Our analyses also included the organic compounds benzene, toluene, ethyl benzene and xylene. These, particularly benzene, are superior indicators of toxicity.

Findings

Study objectives include: 1) Characterize drilling muds and cuttings and identify pollutants, 2) compare hydraulic fracturing fluids with flowback water and identify pollutants, and 3) identify if monitoring wells indicated impoundment leakage.

1. *Characterize drilling muds and cuttings and identify pollutants.* Drilling muds were analyzed as liquids while drill cuttings were analyzed as solids. With the exception of arsenic, mercury, nitrate and selenium, the average concentrations of the primary and secondary drinking water parameters in drilling muds were in excess of all of the inorganic drinking water standards. They also exceeded the drinking water standards for benzene and surfactant (MBAS). Drilling muds contained very high concentrations of sodium, potassium and chloride. TPH (diesel range) was present in all drilling muds. Concentrations ranged from 23 to 315 mg/L.

   Background levels of radiation ranged from 0.005 millirems per hour (mrem/hr) to 0.013 mrem/hr. Sample levels of radiation ranged from 0.009 mrem/hr to 0.016 mrem/hr. The standard for contamination is typically twice background. A review of the individual background levels of radiation indicated that this criterion was not exceeded.

2. *Compare hydraulic fracturing fluids with flowback and identify pollutants.* Four freshwater (makeup water) samples, two hydraulic fracturing fluids and thirteen flowback samples were analyzed. Water quality of water and waste streams deteriorated as gas well development stages progressed. One hydraulic fracturing fluid sample exceeded the drinking water standard for benzene in measurable quantities while ten of thirteen

flowback samples contained benzene in concentrations in excess of the primary drinking water standard of 5 µg/L. Both hydraulic fracturing fluids, all of the drilling muds and flowback samples contained detectable TPH (diesel range). It is important to note, this determination, also known as diesel range organics (DRO) does not indicate that diesel is present. Rather, it indicates that hydrocarbons in the range of C11 to C28 are present. This could include diesel or common hydraulic fracturing fluid additives such as guar gum, an extract of the guar bean used to increase the viscosity of the hydraulic fracturing fluid to efficiently deliver the proppant into the formation. There was no correlation between concentrations of benzene and TPH (diesel range). All flowback samples contained high concentrations of inorganic ions including sodium, chloride, bromide and barium.

Three types of liquids used in the horizontal drilling and hydraulic fracturing processes were evaluated to determine if drinking water standards were exceeded: *Makeup (MU) water* consists of varying proportions of fresh water and recycled flowback water that is mixed with chemicals to make *hydraulic fracturing fluids (HFF)* which are injected into the formation along with a proppant, and *flowback (FB)* is the fluid which returns via the wellhead to the surface after hydraulic fracturing is complete.

Table 1 compares these fluids with regard to their drinking water exceedances. All flowback samples exceeded drinking water standards for barium, chloride, iron, manganese, total dissolved solids and radium 226. Eighty-percent of flowback samples exceeded drinking water standards for gross alpha, beta and radium 228. The organic parameters benzene, toluene, MBAS and styrene exceeded drinking water standards at rates of 77, 23, 15 and 8%, respectively. Selenium exceeded the drinking water standard in 23% of flowback samples while chromium and lead exceeded their drinking water standards in 8% of the flowback samples. Overall, drinking water standards were exceeded for eighteen parameters in the flowback samples.

Six parameters in the hydraulic fracturing fluids exceeded drinking water standards. The hydraulic fracturing fluids in this case consisted of diluted flowback which may explain the presence of contaminants such as barium, chloride, iron, manganese and benzene albeit in lower concentrations than found in flowback. The results suggest that many of the exceedances are the result of contaminants acquired while the fluids are in contact with the Marcellus Formation.

Table 1: Exceedances of Drinking Water Standards

Horizontal Drilling and Hydraulic Fracturing Fluids

- makeup water (MU)
- hydraulic fracturing fluid (HFF)
- flowback (FB)

Water Quality Parameters

- Inorganic (I)
- Organic (O)
- Radioactive (R)

The latter determinations were only available for five flowback samples.

			% exceedances of drinking water standard		
type		drinking water std.*	MU, n=4	HFF, n=2	FB, n=**
I	Ba	a	0%	100%	100%
I	Cl	b	0%	100%	100%
I	Fe	b	0%	100%	100%
I	Mn	b	0%	100%	100%
I	TDS	b	0%	100%	100%
R	Radium-226	a			100%
R	Gross Alpha	a			80%
R	Gross Beta	a			80%
R	Radium-228	a			80%
O	Benzene	a	0%	50%	77%
I	pH	b	50%	0%	38%
I	Al	b	0%	0%	31%
I	Se	a	0%	0%	23%
O	Toluene	a	0%	0%	23%
O	MBAS	b	0%	0%	15%
I	Cr	a	0%	0%	8%
I	Pb	a	0%	0%	8%
O	Styrene	a	0%	0%	8%
I	As	a	0%	0%	0%
I	Hg	a	0%	0%	0%
I	Nitrate	a	0%	0%	0%
I	Nitrite	a	0%	0%	0%
I	Ag	b	0%	0%	0%
I	SO4	b	0%	0%	0%
I	Zn	b	0%	0%	0%
O	Ethylbenze	a	0%	0%	0%
O	Xylene (m,p)	a	0%	0%	0%
O	Xylene (o)	a	0%	0%	0%
R	Uranium-238	a			0%
R	Uranium-238	a			0%

* =primary drinking water standard

* =secondary drinking water standard

** n=5, Radioactive parameters

** n=13, organic and inorganic parameters

3. *Impoundment leakage.* There was no evidence of significant leakage of flowback from the impoundments. Nitrate and lead were detected in monitoring wells in excess of primary drinking water standards. The concentration of nitrite exceeded the maximum contaminant level (MCL) of 1 mg/L in three of five shallow monitoring wells by a maximum of 0.47 mg/L. However, while nitrate exceeded the primary MCL in samples taken after conversion of the impoundments to accept flowback, the single lead exceedance occurred prior to conversion. As is common in West Virginia wells, iron, aluminum and manganese exceeded the secondary drinking water standard in both shallow and deep wells both before and after conversion of the impoundments from holding fresh water to flowback. The impoundment wells did not, however, indicate elevated chloride, bromide or barium concentrations as would be expected if flowback leakage occurred in significant quantities. In addition, while flowback contains measurable benzene and diesel range organics, neither was detected in the monitoring wells. While the monitoring wells detected no contaminants it is not clear that the monitoring interval of 146 days was sufficient to capture any leakage from the impoundments. A longer sampling is suggested with, perhaps, aquifer permeability testing.

Identification of Potential Health Concerns

Three types of water and one solid waste were studied:

- Flowback water
- Drilling muds
- Hydraulic fracturing fluids
- Drill cuttings

Flowback, drilling muds and hydraulic fracturing fluids all exceeded SDWA limits to varying degrees. The extent to which they are properly and safely handled will determine the degree of human exposure via drinking water. An attempt to prioritize the potential for human exposure via groundwater contamination is reflected in **Table 2**. Transported volume and liquid/solid rankings are binomial. It is assumed that exposure increases with volume, particularly to the extent that the material is transported off-site. Liquid contaminants are simply more mobile that any of the solid materials in this study and therefore pose a greater exposure risk.

Table 2: Groundwater Exposure to Shale Gas Waste Streams

Material type	n	transported volume	liquid=2 solid=1	SDWA exceedences primary	SDWA exceedences secondary	SDWA exceedences radioactivity
flowback	13	2	2	18%	47%	85%
hydrofractring fluid	2	1	2	11%	40%	ND
drilling mud(vertical section)	4	1	2	30%	68%	ND
drilling mud (horizontal section)	0	1	2	ND	ND	ND
drill cuttings (vertical section)	10	1	1	NA	NA	NA
drill cuttings (horizontal section)	0	1	1	NA	NA	NA

ND=not determined
NA=not applicable

Some materials could not be sampled and are marked ND for not determined. **Table 2** is not complete as not all of the materials could be sampled during Phase I of the study. With that qualification, flowback yields the highest exposure since: it is a liquid; it is transported off-site; it has multiple toxicities and it is produced in high volume. Hydraulic fracturing fluids are not as toxic as flowback and it is usually prepared on-site, minimizing transportation risk. It may be spilled on the drill pad due to an accident or during a blowout. Proper lining and containment on-site, however, would minimize exposure to groundwater. Both flowback and hydraulic fracturing fluids may escape the wellbore if it is not properly installed and cemented. The risk of migration of these fluids from the target formation to drinking water, considering the distance is remote but not absent. Care must be taken to avoid faults and old gas wells that may conduct these fluids to potable aquifers.

Drilling muds exceeded the primary and secondary SDWA standards more than the previous two water streams; however, its volume is much lower than flowback water or hydraulic fracturing fluids. While drill cuttings will contain contaminants, the volume is generally such that they are easily isolated on-site and taken to landfills for disposal. Therefore, their exposure risk is low if properly handled

This project has significantly improved knowledge of the human health risks associated with shale gas development. As a result, diagnostic tools such as the Br/Cl and Ba/Cl ratios for identifying flowback contamination have been developed. Flowback was identified as the primary waste stream of concern. Practices that prevent environmental and human health exposures are critical. The following are recommended:

- Ensure the integrity of the handling chain for each of the waste streams, identify the weak points and focus the inspectors' attention to those areas.
- Ensure the integrity of wellbores and cement.

Future research should focus on filling out the remainder of **Table 2**. In addition, while the scope of this project is limited to the well development and completion stages of shale gas extraction, future work regarding chemical exposures at the producing well sites would supplement this study.

Recommendations

The liquid and solid wastes generated during shale gas drilling and well completion can be contained and disposed of in a manner that protects human health and the environment. Problems occur when leakage occurs. Leakage points include:

Hydraulic fracturing fluid

- Spillage prior to injection
- Blowout during hydraulic fracturing

Flowback

- The well bore
- Blowout after hydraulic fracturing
- Impoundment failure
- Impoundment leakage
- Fluid spillage at the well site
- Improper disposal

Drilling muds and cuttings

- Storage pit leakage
- Fluid spillage at the well site
- Improper disposal

Major types of waste, cause of release and control mechanisms are summarized in **Table 3**.

Table 3: Control Options for Potential Releases

cause of release	control
HF fluid:	
Spillage prior to injection	Containment for 1 stage volume on drill pad
Blowout during fracking	Primary and backup BOPs
Flowback	
Leakage in the well bore	Hydrostatic well test prior to frac
Blowout after fracking	Primary and backup BOPs
Impundment failure	Follow WVDEP Impoundment Guidelines
Impoundment leakage	Use double polymer liner for pits and impoundments
Fluid spillage at the well site	Containment for 1 stage volume on drill pad
Improper disposal	Enforceable disposal plan
Drilling muds and cuttings	
Storage pit leakage	Use double polymer liner for pits and impoundments
fluid spillage at the well site	Containment for 1 stage volume on drill pad
Improper disposal	Enforceable disposal plan

Recommended Release Control Program

The potential for release of hazardous fluids and solids from drilling and completion operations involves a limited number of substances and release points. A five point release control program that would address the major risks that would affect drinking water is recommended. The following list of control measures should be considered for further refinement:

1. *On-site containment.* A single horizontal well is typically completed with ten hydraulic fracturing stages. A hydraulic fracturing stage includes about one tenth of the typical, total hydraulic fracturing fluid volume of 5,000,000 gallons. The hydraulic fracturing fluid intended for a stage would thus, be about 500,000 gallons. This represents the maximum amount of fluid that could be spilled on the drill pad in a single event. It would be contained within a volume of about 74,000 cubic feet with a safety factor of 1.1 or slightly greater. That would be roughly 150 ft square by 3.25 ft deep.

Flowback may escape via a blowout during a single fracturing stage or leakage during the return period. The former volume could be no greater than the injected hydraulic fracturing fluid volume. Flowback includes the total volume of fluid that flows back out of the well prior to production. Loss of hydraulic fracturing fluids in the formation are typically between 70 and 90% in the Marcellus Formation so the cumulative volume of flowback that reports to the wellhead from a five million gallon injection would be about 150,000 gallons after three weeks. Flowback generally converts to produced water after about six weeks at which time a total of about 200,000 gallons of flowback would have arrived at the surface. This volume would represent about 27,000 cubic feet. In summary, while individual well conditions would differ in degree, a containment volume of 74,000 cubic feet would contain any realistic spill on the drill pad.

2. *Blowout Preventers.* The above scenario allows for flowback to spill on the well pad for up to six weeks without exceeding the recommended containment capacity. In reality, any uncontrolled flowback would be brought under control almost immediately by installation of blowout preventers (BOPs). BOPs may be automatic, responding to drastic pressure changes, or manual. The latter can be engaged in the event the automatic BOP fails.

3. *Wellbore Integrity.* Flowback, as well as production gasses, may escape the wellbore as a result of casing failure or inadequate grouting. Pre-fracturing pressure testing of the wellbore to pressures in excess of the design strength of the wellbore will indicate if adequate wellbore integrity has been achieved. It is recommended the WVDEP select a testing protocol and engineering standard to be applied to all future horizontal hydraulic fractured wells.

4. *Impoundment Integrity*. The pits and impoundment study identified a number of construction shortcomings that would be corrected by simply following WVDEP's guidelines: *Design and Construction Standards for Centralized Pits*, developed by the Office of Oil and Gas in 2011. It is recommended these guidelines be the basis for future construction and inspection/certification.

4. Groundwater monitoring wells were installed to detect leakage from centralized pits as part of this study. The centralized pits employ double polymer liners. No leakage was detected. While the monitoring wells detected no contaminants it is not clear that the monitoring interval of 146 days was sufficient to capture any leakage from the impoundments. A longer sampling is suggested with, perhaps, aquifer permeability testing.

5. *Disposal Plans.* Plans for disposing of flowback, drilling muds and cuttings should specify the type of disposal facility, the facility's name and location and the types and volumes of material to be disposed in each. Documentation of compliance with these conditions should be required as part of the horizontal gas well's permit.

An alternative approach would involve the installation of groundwater monitoring wells around the well development site to allow for groundwater sampling prior to drilling for the establishment of background conditions. Groundwater monitoring can then be performed throughout drilling, hydraulic fracturing and flowback and production stages allowing for potential contamination issues to be more readily identified and corrected. Instituting these recommendations will significantly reduce the risk of accidental release of hazardous solid and liquid wastes associated with shale gas development.

Pits and Impoundments Study

The purpose of studying pits and impoundments was to determine the suitability of the construction and use of these structures in minimizing the potential environmental effects related to horizontal drilling. This task was performed by researchers from the West Virginia University Department of Civil and Environmental Engineering (CEE).

The broad scope of the CEE research included the following areas:

- review of field construction practices
- engineering reviews of approved permit plans for consistency with requirements
- field evaluations to assess the as-built sites with the permitted plans
- limited geotechnical soil property testing
- assessment of data findings related to construction and evaluation of mechanisms for groundwater contamination such as pumps, piping, and geomembrane liners
- preparation of a final topical report of findings

The CEE researchers coordinated with the WVDEP for the review of oil and gas permit files and the selection of candidate sites. A short-list of eighteen sites was provided for review based on a set of CEE criteria that included the age, size, use, construction material and method, and placement of the structure. Certain sites selected were known by the WVDEP to have problems. The selection incorporated sites constructed before and after the enactment of §22-6A in order to assess the implementation and effects of the new regulations on industry practices. Initially, fourteen sites were selected for evaluation, but prior to the completion of the project, one additional site was added, making fifteen total sites visited.

Site Evaluations

Field evaluations and soil property testing were used to ascertain and document the safety and structural integrity of the pits and impoundments. The field observations were performed using an evaluation form developed for the project to maintain consistent data collection across all sites. The evaluation form contained the following sections: permit information, field as-built construction and site conditions, observation checklist, and site operations and maintenance questionnaire. Using this approach, researchers made visual observations of the site and the surrounding environment, documenting items of concern with Global Positioning System (GPS) referenced pictures. Field soil samples were collected using hand shovels at various locations on each site and were subsequently tested in the WVU CEE geotechnical laboratory in accordance with the American Society for Testing and Materials (ASTM) Standards. The specific laboratory soil property tests performed were field moisture content, grain-size distribution and hydrometer analysis, Atterberg limits, specific gravity, Standard Proctor, hydraulic conductivity, and shear strength. Of the fifteen sites evaluated, six were chosen for *in situ* field compaction density and moisture content testing. The laboratory testing and the data collected in the field were compiled and served as the basis for the results of this study.

Permit Review Results

The permit reviews of the candidate sites revealed that the permit files for 10 sites constructed prior to the enactment of §22-6A lacked geotechnical investigation reports. The permits for the three sites constructed after the enactment of §22-6A contained this information. Additionally, the permit information for two sites was not provided by the WVDEP at the time of the evaluation. An analysis of the permits compared the permitted storage volumes with the storage volume requirements of dams as regulated by the WVDEP (WVCSR §22-14 & WVCSR §47-34). No sites were found to meet the requirements of a dam. However, the large quantities of water could be a potential hazard to the public and the environment if a failure were to occur because of the ridge-top location of several sites.

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Laboratory Results

Results of the laboratory testing indicated that none of the post §22-6A sites had soil conforming to the soil types specified by the WVDEP Design and Construction Standards for Centralized Pits. Of the remaining twelve pre §22-6A sites, only one site met the soil standards. However, the laboratory testing indicated that the soil types present at the sites may be suitable for the construction of pits and impoundments if proper compaction is achieved.

An assessment of the soil properties in the available site geotechnical investigations revealed several discrepancies when compared with laboratory data. The soil properties contained within the permit were characteristic of the top layers of excavation, which are not necessarily representative of the soils at the bottom of the excavation. Thus, the engineering properties of the soil tested during the excavation may not be consistent with the properties of the fill material used during construction. Furthermore, the foundation and slope designs of the structure may include soil properties that are not representative of site soil, which can contribute to post-construction issues. For the six sites where *in situ* field compaction density and moisture content testing was performed, the field data was compared with laboratory Standard Proctor density data. This analysis consisted of ascertaining the distribution of field data points in relation to the optimum compaction range for each site. The following areas of concern were identified:

- Three of the six sites had field data points within the optimum compaction range. Two of the sites had 14% of data points in compliance, and the other site had 22% of data points in compliance.
- The field data from the remaining three sites had 0% compliance with the optimum compaction range.
- Based on a total of seventy samples taken across all six sites, only six data points were within the acceptable range (8.5%).
- As a result of insufficient soil compaction density, the slopes of the pits and impoundments have a higher potential of developing subsurface erosion and elevated pore water pressures leading to slope instability.

In summary, the recurring problems and deficient areas from the field evaluations included the following:

- insufficient compaction density of site soil and excessive soil lift height
- surface soil erosion
- slope movement
- buried woody debris
- seepage and wet zones
- geomembrane liner deficiencies
- unsupported pipes

Overall, these deficiencies reflect a lack of adherence to the best management practices set forth in the West Virginia Erosion and Sediment Control Field Manual, as well as poor construction knowledge. These construction practices combined with a lack of field quality control and assurance are indicators of the source and frequency of the problems observed across all evaluated sites.

Operational Review

The Site Operations and Infrastructure Evaluation consisted of a questionnaire for the WVDEP Office of Oil and Gas Inspector and on-site company representative, although the company personnel present at the time of the field visit may or may not have been the principle site inspectors. The responses obtained for each question were compiled for analysis, and trends were established across all sites. The results indicated that none of the WVDEP inspectors had any formal training related to pits and impoundments inspection. In addition, no standardized method was used by the inspectors, which resulted in the use of the state regulations as an inspection guide. Consequently, the inspectors only targeted the readily apparent problems such as slips and slides, while not recognizing, or fully understanding, the smaller problem indicators.

Another area of concern was that the responses from WVDEP inspectors and company representatives revealed that there was no set frequency for site inspections to be performed. The actual frequency of inspections, by the WVDEP or the company, varied from every three days to once every two months, and the inspection frequency by a Professional Engineer (PE) ranged from weekly to never. Infrequent inspections may allow problem areas to go unnoticed or delay corrective actions.

Emergency Action Plans (EAPs) were not required prior to the enactment of §22-6A, and the new regulations stipulate that EAPs are only required for centralized pits and impoundments. The company representative at the post §22-6A sites in this study was not aware that the sites had an EAP, had not received training, and did not know if the EAP had been evaluated for practicality in an emergency situation. Also, at the time of the field visit, the EAP was not available on-site. Therefore, the company representative on-site was unprepared to act in a timely and efficient manner if an emergency situation were to occur.

The EAPs for the post §22-6A sites did not contain any evacuation protocol, with the justification that there were no nearby structures that would be impacted by a failure. No inundation maps were provided in the EAPs to support this statement. During the field evaluations for these sites, a slope failure was found, which is illustrated and described in this report. These site conditions demonstrate the necessity of properly developed and implemented EAPs at Marcellus Shale pits and impoundments.

Recommendations

Based on the findings in the study, the following recommendations were developed:

- Improve WVDEP inspector training requirements and methods.
- Improve the field quality control and assurance for construction and inspection to ensure that the as-built dimensions do not exceed the permitted design.
- Thoroughly test the site soil to determine the geotechnical properties for all fill materials.
- Review the allowable soil type specifications so that suitable soils may be used, or remove the stipulation from the WVDEP Design and Construction Standards for Centralized Pits.
- Develop EAPs for all pits and impoundments, pre and post §22-6A, to improve the safety of these sites.
- Do not allow pre §22-6A sites to be re-permitted as centralized pits or impoundments because the designs do not incorporate §22-6A design standards.

Although there was construction deficiencies noted based on a review of the West Virginia Erosion and Sediment Control Field Manual and the WVDEP Design and Construction Standards for Centralized Pits, none of the deficiencies indicated imminent pit or impoundment failure potential at the time of the site visit. The problems identified do constitute a real hazard and present risk if allowed to progress; but, all problems observed in the field are correctable. Future construction, if done in conformance with the WVDEP guidelines should pose minimal risk.