Environmental Impacts and Countermeasures for Hydraulic Fracturing in Shale Gas Development

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Abstract. Shale gas is a kind of clean and efficient energy resource and chemical raw material. Hydraulic fracturing is the popular technology for extracting shale gas from extremely tight shales by enhancing porosity and permeability. However, the environmental impacts of such technology have aroused public concerns, including earthquakes, water contamination and water consumption and so on. In this article, the author reviewed the main environmental impacts of hydraulic fracturing in the US and China’s shale gas development practice, and then analyzed the mechanism for such possible impacts and the facts in development practice. Furthermore, the author summarized the countermeasures for these environmental impacts and provided advice for shale gas development in environment-responsible manners. The author advised: (1) strengthening science and technology innovation for new fracturing fluids and waste treatment; (2) formulating laws, regulations and standards for evaluation and management; (3) optimizing supervision and management and popular science propaganda.

1. Introduction

Shale gas consists mainly of methane, including little carbon dioxide, and is a kind of clean and efficient energy resource and chemical raw material. Shale gas has great global reserves, most of which are in North America, Asia, Europe, Africa and South America. The US, Canada, China and Argentina are the four main shale gas producing countries. In 2015, the US produced 385.9 billion cubic meters of shale gas, Canada produced 42.4 billion cubic meters, China produced 4.5 billion cubic meters, and Argentina produced 1.8 billion cubic meters. The U.S. produces the most shale gas of the world, boosting itself as the world's largest natural gas producer followed by the Russia. China becomes the largest shale gas producer outside the North America[1].

Shale gas comes from shales buried mainly 1220~3990 meters deep in the US, and 1500~5300 meters deep in China. The shales are characterized by large distribution areas, but with very low porosity and permeability. High-pressure fluid needs to be injected into the boreholes in order to induce fractures and reactivation of pre-existing faults and fractures, and thus enhancing the permeability surrounding the boreholes, which is referred to as hydraulic fracturing. This involves injecting a slurry of high pressure water, sand, and chemical additives, including proppants[2]. Small grains of proppants are pumped into the newly opened fractures to keep them open, allowing shale gas to flow out to the wellhead[2].

However, this development process of such clean energy may have various environmental impacts[3, 4, 2]. The fluid and process of injection and its possible resulting effects, such earthquakes, are the main causes for public concerns, about which there are sharply contrasting opinions[5-7]. China’s shale gas development concentrates in the Yangtze reaches[8], and is expanding from the
upper reaches of the Yangtze river to the middle and lower reaches of the Yangtze river. These areas are also densely populated and facing serious ecological environmental problems. This article aims to provide a rational, objective discussion of the environmental concerns and countermeasures for the environmental impacts to ensure that shale gas is developed in environment-responsible manners[9].

2. Basic characteristics of hydraulic fracturing

2.1. Depths of most hydraulic fracturing
The hydraulic fracturing mainly produces fractures in the shale formations at 1220 meters or deeper. In the US, hydraulic fracturing usually occurs at the depth of 1220~3990 meters, while in China, it usually occurs at depths of more than 2000 meters, such as the first commercial shale gas field in China, Fuling Shale Gas Field[10].

2.2. Scales of most hydraulic fracturing
In China’s shale gas development practice, the heights of hydraulic fractures are usually within 50 meters in the vertical direction, and the horizontal extension widths are usually within 600 meters[11, 12].

2.3. Fluids and additives for hydraulic fracturing
Hydraulic fracturing involves injection of large volumes of water and additives, usually 24~31 thousand cubic meters of water per well and about 1 thousand cubic meters of sand and other additives per well[13]. All these materials are consumed in a few days. Therefore, water consumption of fracturing is characterized by its high water intensity in the early stage. The average water consumption per well in the six major shale gas producing areas of the US is about 11,000 to 15,000 cubic meters[11, 12].

3. Environmental impacts analyses

3.1. Induced Earthquakes
According to the US Environmental Protection Agency, fracturing in mature shale gas development areas can induce micro-seismic events. Injection-induced earthquakes are ubiquitous in conventional deep injection projects, particularly, in areas where natural seismic activity is uncommon and deep injection projects are ongoing[14]. The fractures causing these earthquakes occur at ~2000 meters underground and are usually less than 100 meters in height and less than 600 meters in length. Therefore they has relatively limited impacting areas.

And the seismicity caused by these fractures rarely exceed ML 3[15], for example, half of the wells in the Guy-Greenbrier, Arkansas area induced no detectable seismicity above ML 0, and only a few had events as large a ML 1, and none with ML > 3[3]. Mw 4 is the empirical upper magnitude bound for injection induced seismicity[15], and the physics-based prediction for the maximum size is Mw 2.6[16]. It is concluded that the HF experiment at the Wysin, Poland site did not induce earthquakes Mw>1[17, 2].And the impacted areas by such earthquakes are within 1000 meters from the fractures and thus can not affect ground structures. In fact, only precise equipments can detect such earthquakes.

Furthermore, hydraulic fracturing is a mobile and staged procedure, which exerts a limited influence on the local stress field and the pre-existing faults[17]. The internal geological conditions and external stimulation conditions are impossible to be satisfied simultaneously to trigger the activation of an entire fault and thus induce a destructive earthquake by the relative short-period fracturing although hydraulic fracturing in tectonically active zones pose a higher risk of larger-magnitude earthquake activities[18, 14].
3.2. Water contamination

The additives in fracturing fluids generally account for only 1 percent of the total volume. The additives include drag reducer, surfactant, fungicide and acid, and so on. They pose the main risks of water contamination in case of entering groundwater aquifers[19].

Clean water drilling fluid technology is adopted in vertical wells for the first 1500 meters to avoid contamination of shallow groundwater. And then the drilling hole is cemented with casing to ensure that the drilling hole is completely separated from the environmental water body and the shallow rock body. Compared with the great depth (usually >2000m) at which hydraulic fracturing occurs, the vertical impacted range of hydraulic fracturing is generally limited to less than 100 meters. Taking Fuling Shale Gas Field as an example, the aquifers for water are generally buried no more than 900 meters deep, while the buried depth of the gas-bearing shale is generally 2600 meters or more. They are separated by about 1700-meter-thick formations.

Pre-existing natural fracture systems are the main channels that may connect shale formations and aquifers. Due to the complex underground geological conditions, well leakage may occur and fracturing fluid may enter the overlying formations through cracks, pores or karst caves. However, in practice shale gas well locations must avoid fracture system to obtain better production. In Changning and Weiyuan Shale Gas Field of China, three groundwater pollution monitoring Wells and 18 groundwater monitoring sites for residential drinking water have been set up. So far, no abnormality has been found.

Simulation results show that the upward migration distance of pollutants in vertical wells and horizontal wells without faults is about 950 meters [20]. If the fracturing fluid injected underground is to enter the aquifer, both the tubing production casing and the surface casing need to leak at the same time. The possibility that hydraulic fracturing of deep shale gas will affect the groundwater is less than 2×10^{-8}[21, 22]. Although the environmental impacts of hydraulic fracturing for shale gas development is controllable, countermeasures for reducing such impacts and then making them forever under control in case of major accidents is still needed.

3.3. Water consumption

From the appoint of view of water consumption per well, shale gas wells consume much higher volume of water than conventional natural gas wells. The average water consumption per well in six major shale gas production areas in the US, including Barnett, Fayetteville, Haynesville, Marcellus, Eagle Ford and Permian, is about 11,000~15,000 cubic meters[23]. In China’s Changning-Weiyuan Shale Gas Field, each shale gas well consumes 216,000-28,800 cubic meters water for fracturing. Therefore, if water is collected in relatively small areas during a short period of time, local water consumption will be highly burdened[24].

However, production of shale gas per British Thermal Unit consumes less water than that of coal on average. Water consumption per million British Thermal Unit is 30~80L for conventional oil, 30~50L for nuclear energy, over 9500L for bio-fuels, 8~30L for coal, and only 4~6L for shale gas[9].

As to total water consumption relative to the local total water consumption, it only accounts for 0.1%~0.8% in the US shale gas development regions[23], and in China, the peak daily consumption of water during hydraulic fracturing only accounts for 0.024% of the Wujiang river discharge[24].

4. Countermeasures

4.1. Countermeasures for possible destructive hydraulic induced earthquakes

Before fracturing, the stability of geological structures and surface conditions in the region are fully evaluated, and during fracturing, real-time monitoring is carried out. Micro-seismic monitoring is not only for monitoring micro-seismic events in the process of fracturing to control the impact range of fracturing, but also for monitoring the situation of natural micro-earthquakes before and after fracturing, and evaluating the relationship between fracture-induced earthquakes and natural
earthquakes. The intensity of fracturing can be adjusted according to the monitoring results in order to avoid inducing unexpected, much larger earthquakes.

4.2. Countermeasures for possible water contamination
When planning well sites, operators locate them far enough away from the large fractures and avoid the risk of well leakage from the geological background. During drilling through the shallow formations, gas drilling, water drilling technology and casing sealing are used to prevent drilling fluid from contaminating underground fresh water. And when the drilling bits are penetrating deep formations and gas shales, green chemical agents and degradable fracturing fluids are used. Before fracturing, multi-layer casing cement is used to ensure that no leakage occurs during ensuing fracturing and production. Groundwater quality is monitored before, during, and after the shale gas well operation to get the real-time influence of drilling and fracturing. The treatment process of fracturing backflow is continuously optimized, and the re-use rate of fracturing backflow is continuously increased and thus the discharge of backflow is continuously reduced.

4.3. Countermeasures for water consumption
Although the total volume of water consumed by hydraulic fracturing is relatively small, due to the concentration of production activities in a certain area and the fact that the water-intaking for drilling and fracturing is concentrated in a short period of time, water supply pressure will still exist in the dry seasons or water-deficient areas[23]. Therefore, the water consumption assessment needs to be intensified, and the development procedures needs to be optimized to stagger with dry season and peak water consumption[24]. Enhancing the treatment and management of fracturing fluid, and 100% re-use of drilling wastewater is necessary. In all, it is helpful to carry out water monitoring for shale gas development and comprehensively water planning to reduce water consumption in shale gas hydraulic fracturing process[23].

5. Advice for hydraulic fracturing

5.1. Strengthening science and technology innovation for new fracturing fluids and waste treatment
Technical systems suitable for China’s shale gas development should be set up through scientific and technological innovation. By means of technological innovation, equipment upgrading and process optimization, the adverse environmental impacts of shale gas exploration and development will be controlled to the minimum extent. Optimized fracturing technology may maximize the re-use of fracturing fluid and save water resources. Cleaner fracturing methods, such as pure gas fracturing and liquid gas fracturing, together with non-toxic, harmless and other environment-friendly chemical additives fracturing fluid that can avoid formation pollution are the direction of research and application[25].

5.2. Formulating laws, regulations and standards for evaluation and management
Due to the absence of unified standards and norms, Sichuan and Chongqing shale gas development process learned from the successful experience and practice of shale gas development in other countries, and widely adopted the mature technologies for exploration and development. Policies and regulations suitable for China’s geological, environmental and social conditions should also be formed for the supervision and management of the whole process of shale gas development from drilling exploration to production, from wastewater treatment to the abandonment and sealing of wells. There should be special laws, regulations and standards for well site location, well structure, cementing, fracturing fluids chemical composition, water resource protection, surface wastewater supervision, underground perfusion, etc. And the risk of fracturing induced micro-earthquakes must be included as mandatory content of construction environment evaluation to effectively control the risk. And there must be precise and systematic plans for adjusting the intensity of fracturing according earthquake events to ensure the safety of the working area.
5.3. Optimizing supervision and management and intensifying popular science propaganda

Shale gas drilling site must be optimized to avoid ecologically sensitive areas and vegetation destruction must be minimized. In the later stage, vegetation restoration, soil and water conservation and land re-cultivation must be carried out strictly in accordance with the reclamation plan. And during the whole process, professional teams should be dispatched in each construction link of shale gas exploration and development for supervision to effectively control the occurrence of safety, environmental protection and other malignant events. Necessary penalties must be implemented on operators not in accordance with regulations and standards to avoid the environmental impact of shale gas development.

We should actively carry out popular science publicity to let the public know about shale gas and view shale gas exploration and development objectively. The operators should publicize the chemical reagents used in drilling and fracturing to avoid unnecessary misunderstanding and panic, and be open supervision by the public. During the development of shale gas, the operators should also regularly or irregularly introduce and report the current situation of shale gas development, production technology, environmental impacts such as earthquakes and groundwater pollution risks, and the next plans to the provincial and municipal governments.

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