Integrity of Hydraulic Fracturing Wells During Earthquakes

1. Introduction

Hydraulic fracturing for hydrocarbon recovering, in common with many other processes that involve injection of fluids into the ground, can lead to induced or triggered earthquakes. The ground shaking associated with these earthquakes, and its potential impact on people and buildings in the vicinity of injection wells, is an obvious concern for any hydraulic fracturing operation. Concerns have also been raised, however, regarding well integrity in the event of induced or triggered earthquakes. This document briefly discusses how well integrity might be compromised by earthquakes.

2. Well Integrity and Earthquake Damage

The following text from API (2009) explains the basic concept of well integrity in relation to hydrocarbon extraction through hydraulic fracturing:

> *"The primary method used for protecting groundwater during drilling operations consists of drilling the wellbore through the groundwater aquifers, immediately installing a steel pipe (called casing), and cementing this steel pipe into place. …..The steel casing protects the zones from material inside the wellbore during subsequent drilling operations and, in combination with other steel casing and cement sheaths that are subsequently installed, protects the groundwater with multiple layers of protection for the life of the well.*
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> *The subsurface zone or formation containing hydrocarbons produces into the well, and that production is contained within the well all the way to the surface. This containment is what is meant by the term "well integrity." Moreover, regular monitoring takes place during drilling and production operations to ensure that these operations proceed within established parameters and in accordance with the well design, well plan, and permit requirements. Finally, the integrity of well construction is periodically tested to ensure its integrity is maintained."*

For the purposes of this document, any cracking of the cement, separation of the cement from the steel casing, or deformation of the steel casing may be considered to represent well integrity being compromised, even if none of these would necessarily result immediately in exchange between the fluids in the well and the surrounding groundwater.

Documented cases of hydrocarbon production wells damaged by earthquakes are very few in number although this absence of evidence may not be evidence of absence but simply a consequence of oil and gas companies being reluctant to publicise such events. One instance of casing deformation associated with a seismic event was reported by Green *et al.* (2012) in relation to the Preese Hall shale gas project in Lancashire:

> "*Well-bore deformation was also observed following the first event in April, after stage 2. A caliper log run on 4 April showed that the extent of the deformation was greater than 0.5 inches over a depth range between 8480-8640ft MD.*
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> *The fact that the casing deformation was discovered on 4th April, after the initial seismic event on 1st April, indicates that it is clearly related to the event, which caused rock shear due to the changes in pressure and stress. Rock mass shear, or sideways movement, tends to be concentrated in planes and occurs as a relative lateral displacement across a feature such as a bedding plane, joint or fault. However, little more can be said about this event, due to the lack of available data on the fault or detailed ultrasonic log data taken in the well after the event.*
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> *However, this occurred in the lower section of the reservoir productive zone and subsequent prefrac injection test analysis did not indicate any communication problems between zones, such as cumulative stress or high tortuosity. Such indicators are what might usually be expected as indicators of containment issues due to poor cement. Therefore, well integrity was not considered a risk given the proven integrity of the upper completion, confirmed by surface gas measurements and annular pressure readings…... These tests demonstrate that the integrity of the casing, and the cement, in the upper completion has not been compromised*."

By contrast, reports following much larger earthquakes in Alberta and British Columbia, Canada, in recent years have not indicated any adverse effects on the production facilities and operators were able to resume operations—once regulatory permission was granted—even after a magnitude 4.8 earthquake (Reuters, 2016).

3. Earthquake Effects and Damage to Wells

Damage to surface structures (buildings, bridges, *etc*.) due to earthquake shaking is the result of inertial forces, causing the centre of gravity of the building to move relative to its base or foundation (Figure 1). The damage is actually the consequence of the resulting deformation of the structural elements, and specifically when this exceeds the elastic limit of any structural element. Nearly all earthquake damage is therefore the result of deformation or relative displacement. This is why ductility—the ability to accommodate large inelastic deformations without loss of strength—is such a desirable feature of earthquake-resistant structures to avoid reaching collapse.

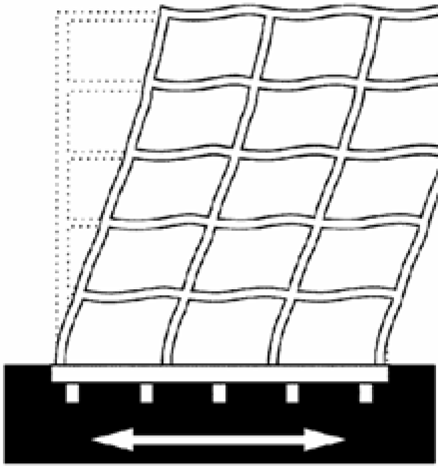

Figure 1. Schematic illustration of how horizontal ground motions leads to vibration in a building and displacement of the structure relative to its foundations, resulting in deformation of the structural elements

For buried structures (whether injection wells, pipelines, or tunnels), inertial response is not an option because of the confinement: there are no vibrations. However, damage can still result from deformation associated with *relative displacements* along or across the structure or component (coherent and uniform movement of the entire component might lead to loss of functionality, if for example connections at the surface were broken as a result, but would not cause damage to the structure/component itself). Buried structures may experience relative displacements due to one of three causes: (a) offset on a geological fault that the structure traverses; (b) liquefaction of the surrounding ground; (c) the passage of the seismic waves along the structure or component. Each of these mechanisms for relative displacement along or across a buried pipeline or well is discussed in the following sub-sections.

3.1. *Fault Slip*

Earthquakes are associated with sudden rupture of geological faults leading the release of stored strain energy in the surrounding crustal rocks; the radiation of this released energy is the source of ground shaking in an earthquake. The fault displacement itself can pose a serious hazard if it reaches the ground surface: a notable example was damage to dam caused by surface fault rupture in the 1999 Chi-Chi earthquake in Tawian. Fault rupture hazard is particularly important for pipelines and other extended lifelines that cannot be relocated to avoid the hazard and therefore must accommodate the potential relative movements (*e.g.*, Melissianos *et al*., 2017). The most successful example of engineering measures to protect pipelines against fault movements is the trans-Alaskan pipeline (surface

rather than buried structure), which survived the 2003 Denali earthquake because of specific measures that allowed relative displacement on the fault to be isolated thus preventing deformations in the pipeline.
For a well drilled vertically into the Earth, fault slip would pose a very serious hazard if the well directly traversed the fault plane (Figure 2). Should an earthquake occur on that fault then the slip would cause deformation and damage to the well.

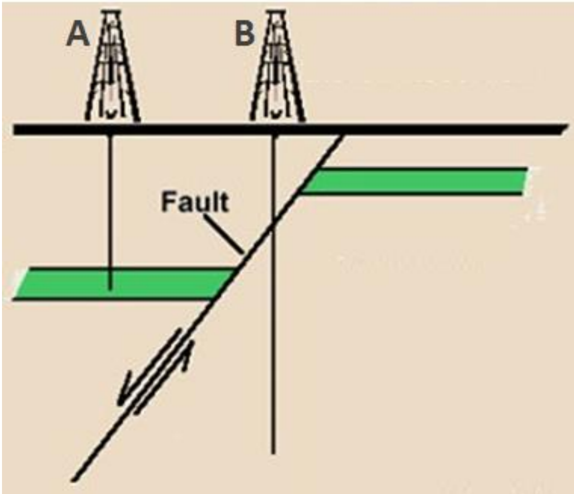

Figure 2. Schematic diagram of two wells in a fault zone; in the event of an earthquake on this fault, well B will clearly suffer damage.

Should fracking in the UK reactivate a fault that is crossed by an injection, this would clearly present a serious threat to well integrity. However, the actual amount of slip is what would determine the extent of the hazard and the risk of losing well integrity. For an earthquake of magnitude 5, the empirical relationship of Wells & Coppersmith (1994) predict a maximum fault displacement of 44 mm. This relationship is derived from field observations and is not calibrated for smaller earthquakes, but if extrapolated to magnitudes 4 and 3, the predicted maximum displacements would be 6.6 mm and 1.0 mm, respectively.

The mitigation of this hazard would be achieved through avoidance of major geological faults when drilling hydraulic fracturing wells, which would be part of the standard procedure anyhow since the chances of triggering a significant earthquake are reduced by injecting at a location remote from any known faults. The report by Green *et al.* (2012) is not entirely clear whether the well deformation associated with the largest earthquake at Preese Hall was directly related to coseismic fault slip.

3.2. *Liquefaction-induced lateral spreading*

Liquefaction is a phenomenon that occurs in saturated sandy soils that involves the complete transfer of overburden stress from the soil skeleton to the pore fluid, with the commensurate increase in pore water pressure and reduction in effective stress. The transfer occurs as a result of the soil skeleton tending to contract (compact) during the earthquake shaking. In a sandy soil, where there is no cohesion between the soil particles, the shear strength is provided by frictional resistance between particles. When the effective stress is zero, the pore pressure pushing particles apart equals the normal stress pushing the particles together, resulting in a complete loss of shear strength. In effect, during shaking episode, the liquefied sand will behave as a liquid, and structures may sink into the ground (Figure 3) and buried structures may rise to the surface. If there is a free-face, such as a river channel, close to the site of liquefaction, overlying layers of soil may slide towards the opening, which is a phenomenon known as lateral spreading (Figure 3).

Figure 3. Effects of soil liquefaction. *Upper*: A building sunk into liquefied ground; *Lower*: Liquefaction-induced lateral spreading causing damage to bridge piers.

If liquefaction occurs in a sand layer at some depth below another non-liquefiable layer and this leads to lateral spreading, any vertical structures buried in the ground will experience deformation. This is an issue that has been addressed most commonly with piled foundations (*e.g.*, Bray & Ledezma, 2007) as illustrated in Figure 4. A hydraulic fracturing well subject to lateral spreading could be expected to respond in the same way and this would clearly pose a threat to well integrity.

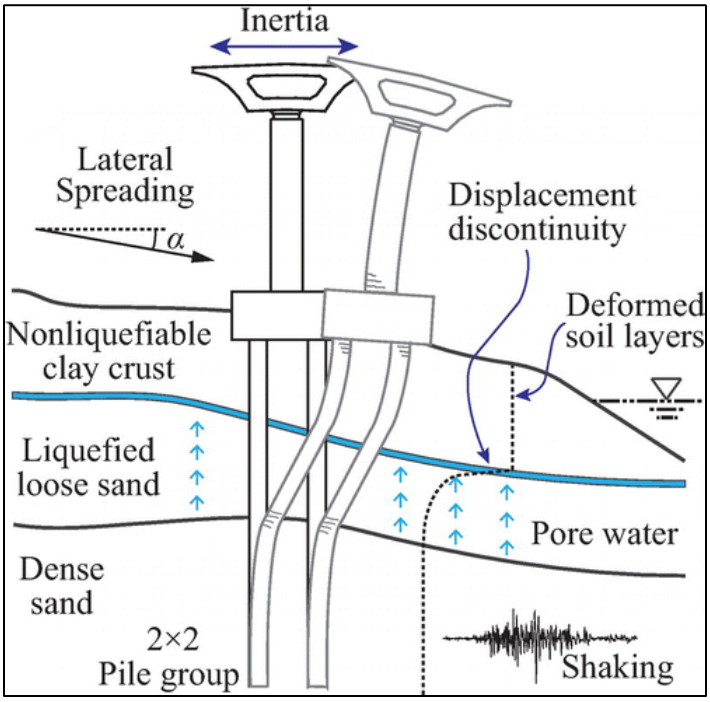

Figure 4. Schematic illustration of piles below a bridge pier being deformed by lateral spreading of a liquefied sand layer

In terms of the likelihood of this particular hazard affecting a hydraulic fracturing operation in the UK, a few observations are in order. The first is that liquefaction is generally confined to, at most, the uppermost 15 metres and significant lateral spreading will generally be associated with liquefaction at even shallower depths. The most relevant observation is that even in closely studied cases, such as recent earthquakes and their aftershocks in New Zealand (*e.g.*, Quigley *et al*., 2013), there are no reported cases of observed liquefaction effects due to earthquakes smaller than about magnitude 4.5.

3.3. *Wave-induced ground strain*

The passage of seismic waves causes deformation of the ground, which in turn can deform any buried structures. The deformation is generally elastic, meaning that the ground returns to its original position after being displaced by the passing of the earthquake waves. There are two main types of waves that propagate from the source of an earthquake, these being P-waves (which are like sound waves) and S-waves. The energy in the waves advances by displacing particles of the ground, passing the kinetic energy from one particle to the next. A P-wave advances by particle disturbance along the same direction at the wave is travelling, whereas an S-wave causes particle movement perpendicular to the direction of wave travel (Figure 5). Two different velocities can be defined, one being the propagation velocity, which is the speed at which the wave front advances; the propagation of P-waves is greater than that for S-waves. The second velocity is the particle velocity; the maximum value of the particle velocity during the passage of the seismic wave train is PGV.

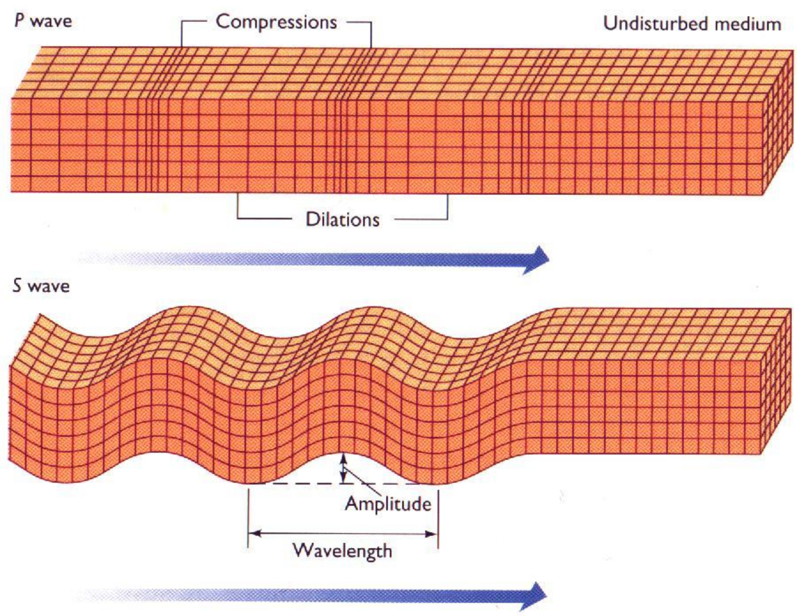

Figure 5. Propagation modes of P-waves and S-waves

The propagation velocity depends on the material properties of the ground: the stiffer the rocks or soil, the more rapidly the seismic waves advance. The particle velocity depends on the energy in the seismic waves, which will be a function primarily of the magnitude of the earthquake (which is related to the amount of energy released) and the distance from the seismic source (which determines how much the energy will have dissipated). Since the ground generally becomes stiffer with depth, propagation velocities tend to be lower near the surface and increase downwards. As a seismic wave travels upwards from a high-velocity layer to a layer of lower velocity, its travel path will be bent towards the vertical (refraction). For this reason, it is generally assumed that near the ground surface, seismic waves propagate vertically upwards (Figure 6). Therefore, a vertical well will be exposed to longitudinal strain from the passage of P-waves and lateral strain due to the passage of S-waves. The ground strain can be estimated from the ratio of PGV to the propagation velocity; since S-waves generally carry greater energy and propagate more slowly than P-waves, the lateral strain is likely to be greater. Concrete and steel have yield strains on the order of 0.2%, which means that in the presence of soft soils near the surface—for which propagation velocities might be on the order of 200 m/s—a PGV of 40 cm/s would be required to induce this level of strain. Such levels of PGV are associated with much larger earthquakes (M > 6.5) than those expected from hydraulic fracturing (Figure 7). At greater depths, within rock (where propagation velocities exceed 1 km/s) the amplitudes of particle velocity would be much lower—it doubles at the surface—and consequently the possibility of exceeding strain limits for the wells is extremely low.

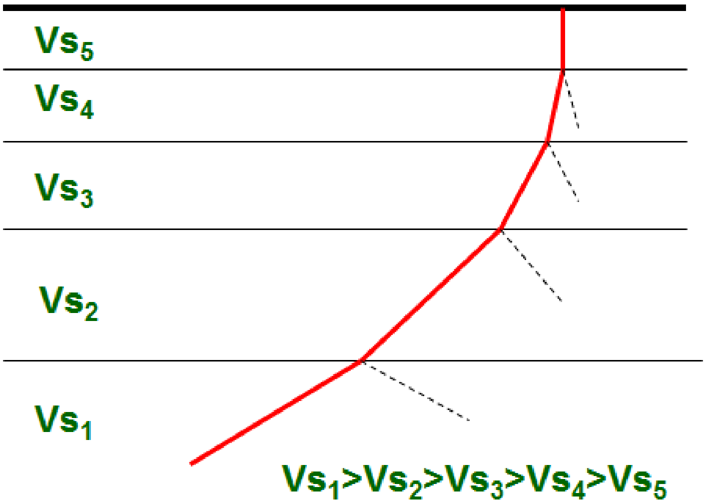

Figure 6. Propagation of an S-wave upwards through layers of decreasing velocity near the ground surface; the wave path, indicated by the red lines, is refracted into a near-vertical direction. The dashed lines indicate the wave energy reflected from the interface between the layers

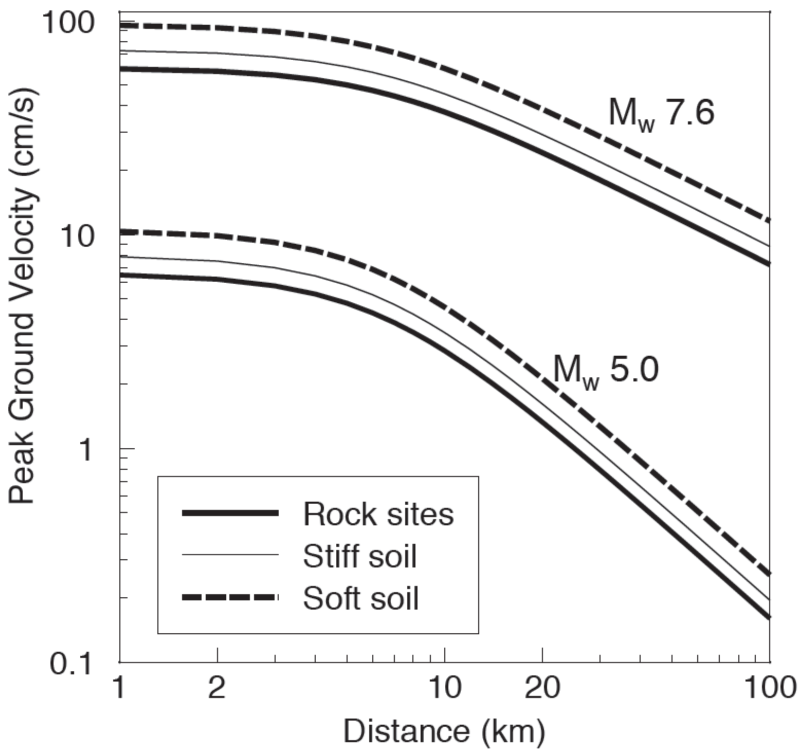

Figure 7. Predicted PGV values (in cm/s) as a function of magnitude, distance and site classification (Akkar & Bommer, 2010)

4. Discussion and Conclusions

Although some deformation of the well casing at Preese Hall was reported to have been caused by the magnitude 2.2 earthquake that led to suspension of that operation, the cause of this deformation is not well understood. The deformation appears not to have compromised the well integrity in any way.

Hydraulic fracturing wells could be damaged by an earthquake if the well traverses the fault generating the earthquake. Damage could also result from liquefaction-induced lateral spreading, but this could only occur if the well crosses a layer of saturated sand and there is a nearby free face to allow the lateral movement. Even where such conditions were encountered, it is very unlikely that significant lateral spreading could occur unless the earthquake were of at least magnitude 5. The passage of seismic waves can also cause deformation of the well casing but it would probably require a large earthquake—greater than even the largest tectonic events that have occurred in the UK—to result in damage to the well.

5. References

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