Injection of solids to lift coastal areas

BY LEONID N. GERMANOVICH1 AND LAWRENCE C. MURDOCH2,*

1Department of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Drive, Mason Building CEE, Atlanta, GA 30332-0355, USA
2Department of Environmental Engineering and Earth Science, Clemson University, 340 Brackett Hall, Clemson, SC 29634, USA

Catastrophic flooding in coastal areas is an ongoing problem that may be aggravated by projected sea-level rise. We present a method of flood protection called SIRGE (solid injection for raising ground elevation), where the ground surface is raised by injecting sediment-laden slurry into hydraulic fractures at shallow depths. The injection process is repeated at adjacent locations to create a network of sub-horizontal, overlapping injections of solid material (hydraulic fractures). We argue that injecting sediment over large lateral distances would cause a lasting surface uplift that scales with the thickness of injected sediment at depth. We support this concept by an analysis showing that, in contrast to hydraulic fractures in petroleum reservoirs, hydraulic fractures in soft, shallow formations would typically grow in the toughness-dominated regime. It appears that the SIRGE process could be implemented to lift ground elevations in places such as Venice or New Orleans. Experimental and geological examples indicate that hydraulic fractures of suitable orientation and size can be created in areas with appropriate in situ stresses.

Keywords: hydraulic fracture; flood protection; ground uplift; coastal areas; solid injection

1. Introduction

Widespread press coverage has etched into the minds of a generation images of the devastation in New Orleans following hurricane Katrina in 2005, but scores of less-publicized storms regularly inundate coastal areas around the world. Global data indicate a 30 year trend towards more frequent and intense hurricanes (Webster et al. 2005) with more destructive potential (Emanuel 2005). Modern strategies for protecting coastal areas (electronic supplementary material, appendix A) are commonly based on creating barriers to encroaching water, such as the New Orleans levee systems or the Dutch dikes (Pugh 2004). This approach is vulnerable to catastrophic failure, however, as evidenced by the deaths and damage left after Katrina (Kates et al. 2006), and this vulnerability is expected to increase should the eustatic sea level continue rising (Pugh 2004).

*Author for correspondence (lmurdoc@clemson.edu).

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Raising areas above the reach of floodwater is an alternative to erecting barriers. In 1900, Galveston, TX, was struck by a category 4 hurricane that left 8000 dead and decimated buildings and infrastructure (Frank 2003). To rise above the threat of future storms, the city decided to permanently elevate 500 city blocks behind the seawall (electronic supplementary material, appendix A, figure A1a). This was accomplished by raising buildings up to 5 m by mechanical jacks and then filling the space under them with dredged sediment (electronic supplementary material, figure A1). Galveston has since been hit by many hurricanes and storms—including Rita in 2005 and Ike in 2008—but a repeat of the 1900 catastrophe has been avoided. A similar strategy was used to elevate the street level in Chicago by up to 3 m after problems of drainage and sewerage disposal caused a cholera outbreak that killed 6 per cent of the population in 1854 (Andreas 1975).

Raising the closely spaced historic buildings of Venice using mechanical jacks has also been suggested (Project Rialto; BAMS 2008; Sandri 2008). Another approach to raising Venice is based on the poroelastic effect produced by the subsurface injection of sea water (Comerlati et al. 2004; Castelletto et al. 2008). Vertical displacement resulting from an increase in pore pressure $\Delta p$ is approximately

$$w = \frac{1 - 2\nu}{2G(1 - \nu)} \alpha b \Delta p,$$

(1.1)

where $b \approx 200$ m is the aquifer thickness, $\nu$ is the drained Poisson’s ratio, $G$ is the shear modulus, $\alpha \approx 1$ is the Biot–Willis coefficient and uniaxial strain is assumed. Expression (1.1) follows directly from the constitutive law for poroelastic materials (equation (6.2) below). The fraction term in equation (1.1) is the uniaxial compressibility of the aquifer, which is estimated to be approximately $10^{-9}$ Pa$^{-1}$ (Comerlati et al. 2004, fig. 5). Numerical simulations of the injection process (Comerlati et al. 2004) suggest that the pore pressure would increase by approximately $\Delta p = 1.2$ MPa in 10 years.

Values cited above indicate an expected displacement of 24 cm, according to equation (1.1), consistent with the uplift of 10–40 cm resulting from detailed finite-element analyses (Comerlati et al. 2004). Therefore, the total displacement achieved using the poroelastic effect is probably limited to fractions of a metre for reasonable combinations of variables in equation (1.1). The values of $b = 200$ m and $\Delta p = 1.2$ MPa used with equation (1.1) correspond to favourable conditions underlying Venice, and they likely will be less in other settings. Galveston required up to 5 m of uplift, and displacements of similar magnitudes would have been needed to protect many areas that had suffered from cyclonic storm surges (Pugh 2004, table 6.1). It seems unlikely that displacements of this magnitude could be achieved by deforming sediments poroelastically.

The benefit of raising elevations as a means for protecting cities from flooding is clear, but the best method for accomplishing this uplift remains an open issue. We suggest that there is an alternative that can achieve the magnitudes and permanency of the Galveston Grade Raising, with the logistical advantages of the poroelastic technique proposed for Venice. Our alternative resembles the poroelastic technique in that it uses wells to inject fluid and cause displacements. It differs from the poroelastic technique in one simple but important way: solid material is mixed with the injected fluid. The injected solids would support subsurface grains; hence, displacements would persist after pore pressures have
dissipated. Repeated injections of solids will build up displacements, and the cumulative uplift can in principle exceed that achievable by poroelastic methods. In contrast to the Galveston Grade Raising, however, this alternative would inject the solid material at depth instead of using it to fill beneath artificially elevated buildings, obviating the need to raise buildings on jacks.

In this paper, we describe the concept of raising ground elevations using hydraulic fractures filled with solids, and evaluate it using theoretical analyses and existing data. We call this process solid injection for raising ground elevation or SIRGE.

2. Solid injection for raising ground elevation

(a) Hydraulic fracturing

Injecting solids into the subsurface is routine in the energy, geotechnical and environmental industries. Grout injection to seal permeable horizons is one example (Hausmann 1990). The injected solid grains are much smaller than pores in the subsurface and may simply flow through the pores like a liquid. By contrast, hydraulic fracturing creates a relatively large opening, a fracture, which can be filled with coarse solid grains (Economides & Nolte 2000) larger than the subsurface pores. Hydraulic fracturing methods are widely used to inject sand into oil or gas reservoirs because the resulting sand-filled hydraulic fractures significantly increase hydrocarbon production (Economides & Nolte 2000). Hydraulic fractures are created down to depths of 5 km or more for energy applications, but they are also created at much shallower depths, less than 100 m, to improve environmental remediation or for geotechnical operations (Lutenegger 1990; Murdoch et al. 1991; Hamouche et al. 1995).

The basic process of hydraulic fracturing (figure 1a) involves injecting a fluid at rates that are fast enough for the injection pressure to increase above the threshold value required for fracture nucleation (Economides & Nolte 2000; Jaeger et al. 2007). Fracture propagation creates a broad, thin opening by displacing the enveloping formation normal to the plane of the fracture. The aperture of a fracture is the difference of normal displacements of the fracture walls. Solids are suspended in a liquid and injected as a slurry to fill the fracture during propagation (figure 1a). The fracture walls start to close when the pressure decreases following injection, but the injected solids hold the fracture open to provide persistent displacement (figure 1b). For SIRGE purposes, this process would be repeated to superimpose multiple fractures to achieve the necessary total displacements (figure 1c).

(b) Orientation and uplift

The orientation of hydraulic fractures can range from horizontal to vertical, and this can play an important role in the magnitude of displacement at the ground surface. Hydraulic fractures that are small relative to their depth cause only minor displacements at the ground surface. The fracture simply deforms the enveloping material in this case. A fracture starts effectively lifting its overburden when it grows to a total size that is similar to its depth. When it grows to several times larger than its depth, a flat-lying fracture will lift the ground surface by an amount roughly equal to its aperture (Pollard & Holzhausen 1979;
Figure 1. (a) Mixing and injecting a slurry to create a hydraulic fracture. (b) Opening of hydraulic fracture causes uplift at the ground surface. (c) Multiple sub-horizontal hydraulic fractures and multiple wells superimposed to lift large area.

Germanovich & Lowell 1995; Dyskin et al. 2000; Murdoch & Slack 2002; Murdoch et al. 2006). As a result, creating a persistent aperture by injecting solids can create lasting displacements of the ground surface when a hydraulic fracture is roughly flat lying and several times longer than its depth. The fracture shown in figure 2, for example, was created at a depth of 1.5 m and it grew to approximately 6 m. Uplift of roughly 2 cm was observed, similar to the thickness of sand in this fracture (Murdoch et al. 1991; related data are in Murdoch et al. 2006).

Vertical hydraulic fractures, which cause only minor uplift of the ground surface, have limited applications in the SIRGE process. Thus, the orientation of hydraulic fractures is important to the viability of this approach. The in situ state of stress is generally recognized as the most important factor controlling orientation, and hydraulic fractures are expected to be perpendicular to the direction of least principal compressive stress (Amadei & Stephansson 1997). Gently dipping orientations of hydraulic fractures are generally expected, where the ratio of horizontal to vertical stress, $\sigma_h/\sigma_v$, is greater than 1, whereas steeply dipping fractures are expected where $\sigma_h/\sigma_v < 1$.

In situ stress state results from the geological history of an area and varies laterally, with depth, and with subsurface material (Zoback 2007). Commonly, the stress ratio is greater than 1 in un lithified material at depths of a few metres, but in many locations it decreases and is less than 1 at depths below approximately 10–20 m (e.g. Hamouche et al. 1995). The stress ratio in rock, however, is generally greater than 1 at depths of tens of metres and it decreases to 1 at a depth of approximately 300 m, according to data presented by
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Haimson (1977), Amadei & Stephansson (1997) and Jaeger et al. (2007) among others. Many rocks were once deeply buried, where they were highly stressed by the overlying material. Uplift and erosion removed overburden and reduced the vertical stress, but the horizontal stress remains elevated. This type of loading history elevates the stress ratio (Amadei & Stephansson 1997). Retreat of glaciers causes unloading that can favour high stress ratio and horizontal hydraulic fractures even in un lithified sediments at depths below 50 m (Lutenegger 1990). Yet, in many locations, shallow un lithified material may have never experienced a stress greater than that caused by the current overburden, resulting in $\frac{\sigma_h}{\sigma_v} < 1$.

Continuous profiles of stress state through multiple geological units at a single location are rarely available. Based on inference from measurements at different locations, however, we expect that stress ratios $\frac{\sigma_h}{\sigma_v}$ generally decrease with depth but may increase across an unconformity (a contact separating rock units with different geological histories). For example, the contact between un lithified sediments and underlying bedrock is an unconformity. This is important because it means that the decreasing stress ratio at shallow depths in un lithified material cannot necessarily be extrapolated below the contact with underlying material of a different age and stress history. For instance, stress measurements or behaviour during geotechnical operations in the surficial Holocene sediments underlying New Orleans (Kolb & Saucier 1982) probably cannot be extrapolated to the underlying deposits, where the stress ratio $\frac{\sigma_h}{\sigma_v}$ has likely been increased by consolidation and subaerial exposure during the Pleistocene.

Rock stratification and contrasts in material properties may also affect fracture orientation and containment (e.g. Germanovich et al. 1997). Anisotropy and contrasts in elastic moduli between adjacent beds are likely to affect stress state (Amadei & Stephansson 1997) and may favour flat-lying orientations of hydraulic fractures (Kavanagh et al. 2006). If the strength contrast between the layers is small, permeability contrasts may contain vertical hydraulic fractures in soft materials within a low-permeability bed (de Pater & Dong 2009) because leakage of liquid out of the fracture hinders growth into an adjacent permeable layer. This raises the possibility that a high-permeability sand bed may inhibit the upward growth of a hydraulic fracture in an underlying fine-grained bed.

Therefore, stress states indicate that shallow hydraulic fractures in rock will typically be horizontal, a favourable orientation for SIRGE, whereas the stress state in recent, shallow sediments may favour hydraulic fractures that are steeply dipping, an unfavourable orientation. Older sediments, which have once been subjected to stresses greater than the current load, may have $\frac{\sigma_h}{\sigma_v} > 1$ that results in favourable orientations. Interbeds of sand and clay may also create conditions in which flat-lying hydraulic fractures are created. Hence, it appears that hydraulic fractures with suitable orientations could be created in a variety of locations, although we recognize that geological conditions may cause fracture orientations to be unsuitable in some places.

3. Example

It will be worthwhile to sketch an example of how the SIRGE process could be applied to elevate a broad area of a city. The approach will be to describe an implementation over a square kilometre, which could be repeated as needed. In this example, we consider producing an uplift rate of approximately 1 mm d$^{-1}$.
Figure 2. Hydraulic fracture created in silty clay near Cincinnati, OH. Maximum thickness of injected sand is approximately 2 cm (inset), which correlates well with the observed surface uplift.

(a) Basic configuration

Consider a grid of 100 wells laid out on 100 m centres (figure 3). This spacing is similar to the size of city blocks, such as in Venice or New Orleans. Suppose that sediment is injected as a slurry into 10 wells at any given time, while the other 90 wells are allowed to equilibrate from previous injections. The wells used for injection would be switched regularly to distribute sediment over the entire grid.

The depth of the wells is assumed to be equal to the grid spacing, approximately 100 m. Flat-lying hydraulic fractures growing from one well are expected to overlap with fractures created from neighbouring wells and to interact with the ground surface when their size is approximately equal to their depth. For the sake of this example, we assume that the fractures are filled with slurry containing a 30 per cent volume fraction of solid phase because similar material is pumped routinely for environmental projects (Wong & Alfaro 2001; Murdoch & Slack 2002). The 30 per cent volume fraction of solids provides a reasonable factor of safety below the critical volume fraction of approximately 60 per cent (e.g. Frankel & Acrivos 1967; Abulnaga 2002), when particles interlock to create a nearly solid mass that is all but impossible to pump. This volume fraction of 30 per cent corresponds to approximately 50 per cent bulk solids, which means that half the injected volume will support the fracture walls and sustain uplift, while the other half is water that eventually leaks out of the fracture. Each fracture is designed to intersect or overlap with its neighbours, so the ensemble system will behave mechanically as a large fracture (inclusion) approximately 1000 m across and 100 m deep (figure 3b). Therefore, a net uplift rate of 1 mm d$^{-1}$ would require a total pumping rate of 2000 m$^3$ d$^{-1}$ or $Q = 200$ m$^3$ d$^{-1}$ per injection well.
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sediment-laden slurry from dredge

water returned

sediment–water separator and pump

coverage from each well

trunk line

wells along branch line

cross-section view showing wells and injected area with 10m of uplift (hatched area) using no vertical exaggeration. New Orleans skyline at approximately the same scale.

Figure 3. (a) Plan view showing fractures (shaded) and wells and pipes used to inject slurry. (b) Cross-section view showing wells and injected area with 10m of uplift (hatched area) using no vertical exaggeration. New Orleans skyline at approximately the same scale.

(b) Fracture characteristics

Basic fracture characteristics, such as diameter, average aperture and injection pressure, will be affected by properties of the enveloping formation and injected fluid. We further assume that the viscosity of the water-based slurry (frac fluid) is $\mu = 100\text{ cP}$ and that it contains a mixture of clay and coarser sediment at $\phi = 30\%$ solid particles by volume. The viscosity of the liquid phase (water) would probably need to be thickened somewhat in order to transport sand-sized grains and limit screen-outs (Economides & Nolte 2000). A few per cent of clay increases viscosity by two to three orders of magnitude (Parsons et al. 2001), and this amount of clay is common in sediments (e.g. Iverson 1997). The solid content of 30 per cent is sufficiently high for the final thickness of the injected layer to be a substantial fraction (approx. half) of the fracture aperture. Yet, it is significantly lower than the critical volume fraction to avoid the sudden increase in viscosity that could render the slurry unpumpable.

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SIRGE fractures are typically expected to be created in unlithified sediments such as those underlying New Orleans (Kolb & Saucier 1982) and Venice (Simonini et al. 2007), although some applications may involve hard rocks (e.g. underlying New York City). An analysis of hydraulic fractures created in shallow unlithified formations that can be characterized by fracture toughness, $K_{IC}$, is outlined in §5. Here, we adopt that analysis to estimate fracture characteristics.

For the sake of example, we consider the fluid leak-off into the host material as negligible at the time scale of fracture propagation (although it may be considerable at much larger time scales). We use Young’s modulus of the formation, $E = 100$ MPa, and Poisson’s ratio, $\nu = 0.35$, to estimate fracture dimensions for different values of $K_{IC}$. It appears that, for $K_{IC} = 0.2$ MPa $\times$ m$^{1/2}$, hydraulic fractures would reach a radius of 55 m and average aperture of $w_0 \approx 2$ cm after 24 h of injection. This corresponds to approximately 1 cm of average thickness of injected solids after the water dissipates from the fracture into the formation. Fractures of these dimensions will overlap as shown in figures 1 and 3, and will create an average uplift rate of approximately 1 mm d$^{-1}$. Parameters used in this example ($K_{IC} = 0.2$ MPa $\times$ m$^{1/2}$, $E = 100$ MPa, $\nu = 0.35$) are within the currently expected range for shallow subsurface materials (§5), so we conclude that it should be possible to create fractures of dimensions suitable for SIRGE applications.

The net (driving) pressure will decrease sharply from a megapascal level early in injection to 100 kPa after 1 min and only 25 kPa after 24 h. This suggests that, most of the time, the injection pressure required at the ground surface will be only slightly greater than $(\rho - \rho_{sl})gh$, where $\rho = 2200$ kg m$^{-3}$ is formation density, $\rho_{sl}$ is slurry density and $h = 100$ m is the depth. Slurry density will be $\rho_{sl} \approx 1500$ kg m$^{-3}$, when the density of solid particles is 2600 kg m$^{-3}$ and their volume fraction is $\phi = 30\%$. Because the driving pressure is negligible, ignoring friction in pipes results in the pumping pressure on the surface being 0.7 MPa. This indicates that the total power required to pump the slurry can be estimated as $NQ_0(\rho - \rho_{sl})gh \approx 16$ kW for the array of $N = 10$ wells.

(c) Fracture propping and net uplift

The slurry injection cycles into each well once every 10 days in our example. This time is chosen based largely on operational considerations (there are 10 wells in each line), but it is also intended to provide time for the excess water to flow into the formation, so that the fracture walls can close and be propped open by injected solids before the next injection. For example, pressures during compensation grouting operations in Singapore marine clay dissipated nearly completely during a 3 day rest period between injections, according to Addenbrooke et al. (2002). Also, estimates in §5c suggest that it may be feasible to create fractures in which the leak-off is slow enough to avoid problems with screen-outs during propagation, but fast enough to dissipate most excess water between injections.

The configuration outlined above would create 1 mm of net uplift (i.e. uplift supported by solids) per day over 1 km$^2$. This amounts to an uplift of 1 m in 3 years, or 10 m in 30 years with continuous operation (figure 3b). This is roughly the same rate as the Galveston Grade Raising, except that the SIRGE method would be largely transparent to residents. In New Orleans, this design would significantly reduce flood risks in 3 years because 1 m of displacement would
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raise the average elevation to equal to or above mean sea level. Ten metres of
displacement would raise elevations to nearly equal to the level of the worst case
scenario storm surge predicted for nearby Gulfport, MS (Russo (1998, table 1)
gives this level as 11 m). A more modest approach would be to inject sediment at
a slower rate sufficient to keep pace with subsidence of approximately 8 mm yr\(^{-1}\)
(Dixon et al. 2006). This would prevent subsidence from degrading the level
of safety currently provided by the levee system. The uplift required to benefit
Venice (Comerlati et al. 2004) is approximately one-tenth of that required in New
Orleans (Russo 1998), so injection rates in Venice could be slower, or injection
locations could be deeper and more widely spaced, than outlined above and
shown in figure 3.

The design requires equipment, logistics and operational skills that are similar
to those available within the geotechnical and petroleum fields. For example, in
1998–2002, BP injected 2 million tons of petroleum drill cuttings and open pit
materials into a soft cretaceous sandstone on the North Slope of Alaska (Guo &
Abou-Sayed 2007). Typical operations involved injecting slurry into one of the
three wells continuously for a number of days and then switching injection to
another well. Chevron recently disposed of more than a million barrels of pit soil
and canal bottoms into a single well in Port Fourchon (approx. 50 miles south of
New Orleans) during 2 years of injection (Reed et al. 2002). To create a slurry,
solid waste was mixed with water, and injections took place for 11 hours a day,
5 days a week. This is similar to the SIRGE parameters, although solid wastes
were injected into a weakly consolidated sand formation located at much greater
depths of 4400–5000 ft.

The example (figure 3) suggests that the SIRGE process could create a
beneficial effect with available technology in a reasonable time frame, and
our mechanical analysis suggests that fractures with appropriate characteristics
could be created. Two key questions remain unanswered, however: How much
will it cost? and Will it work? Cost depends upon social needs, geographic
region, political factors and many other aspects. In the electronic supplementary
material, appendix C, we give an example showing that SIRGE may be
economically viable compared with current alternatives. Below, we concentrate
on fundamental physical conditions that constrain applicability of SIRGE.

4. Processes similar to SIRGE

Field experiments and engineering applications provide examples of methods
similar to SIRGE, but implemented at a small scale, whereas the geological record
provides examples of similar processes that occur naturally at a larger scale.

(a) Hydraulic fractures in soil

Properties of soil range widely, depending on composition, grain size, water
content, cementation and other factors. It is possible that some combination of
these factors results in properties where hydraulic fractures cannot be created, but
experimental evidence suggests otherwise. For example, laboratory experiments
using silty clay showed that hydraulic fractures could be created (figure 4a)
by injecting fluid into samples with water contents ranging from 0.17 to 0.33
Figure 4. Examples of hydraulic fractures in soft materials. Scale bars are 2 cm. (a) Glycerine with rhodamine dye (red) injected into wet clay. Lag zone occurs between the red staining and the leading edge of the fracture marked by the dotted line. (b,c) Viscous slurry (paste) injected into Georgia red clay (b) and silica flower (c). The liquid flow is localized in thin, propagating, crack-like conduits resembling hydraulic fractures (Chang et al. 2003; Chang 2004; Germanovich et al. 2007). The shape of (c) resembles sand diking (Shoulders & Cartwright 2004).

(Murdoch 1993). At the low end of this range, the soil is relatively stiff and brittle, whereas at the high end it is soft and plastic. Nevertheless, despite this diverse range, injecting glycerin always produced a thin, sheet-like feature that could be simulated using techniques from fracture mechanics and the concept of fracture toughness (Murdoch 1993).

It is possible that cohesion enabled fractures to form in the experiments by Murdoch (1993), but fracture-like features are known to form even in materials that have little or no cohesion (figure 4b,c). Recent experiments (Chang et al. 2003; Chang 2004; Hurt et al. 2005; Germanovich et al. 2007) involved injecting viscous slurry into dry or water-saturated, inert-particulate material, which was removed after the fracturing fluid hardened. The resulting features were generally sheet-like and formed normal to the least principal compression. Features with similar geometries were also formed by injecting various fluids into unconsolidated sediments (Ito et al. 2008), loose sand (Khodaverdian & McElfresh 2000; Di Lullo et al. 2004; de Pater & Dong 2009), poorly graded soil (Elwood 2008), clay samples (Au et al. 2003; Soga et al. 2004) and siliceous powder (Chang 2004; Galland et al. 2006). Although the geometries of these features resemble fractures, the mechanics by which they form is likely to be different from classical fracture mechanics (Khodaverdian & McElfresh 2000; Chang et al. 2003; Chang 2004; Di Lullo et al. 2004). In particular, the cohesionless material must be in compression everywhere, as it cannot support the localized tension assumed to develop at the tip of a growing fracture in a material with cohesion (Chang et al. 2003; Hurt et al. 2005; Germanovich et al. 2007). The development of theory to explain the mechanics of fractures in cohesionless and weakly cohesive materials is ongoing (e.g. Hurt et al. 2005; Germanovich et al. 2007; Huang & Wu 2008; de Pater & Dong 2009; see also §5), but the experimental evidence for the creation of these features appears to be well established.

(b) Field experiments

Hydraulic fractures created at shallow depths have useful environmental applications and for this reason their form has been investigated in some detail (Murdoch 1995; Wong & Alfaro 2001). For example, fractures have been created
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Environmental hydraulic fractures demonstrate that solids can be injected in a roughly flat-lying geometry that causes uplift over an area that is broad relative to its depth. Since displacement over a single fracture is dome-like (Murdoch et al. 2006, fig. 5), multiple superimposed injections would be needed to create a sufficiently uniform displacement.

A pilot test of ground-lifting by multiple injections of solids was conducted in 1971 and 1972 on the island of Poveglia (figure 5a), near Venice, Italy (Marchini & Tomliolo 1977; Gallavresi & Carbognin 1987). The Poveglia test consisted of injecting slurry into 78 boreholes distributed within an area of 900 m².
and extending to a depth of 10 m (figure 5b). Boreholes were spaced roughly 2.5 m apart around the periphery and 5 m apart inside the test area (figure 5c). The test site was underlain by fine-grained sand, silts and clay to a depth of 10 m, where a sandy bed provided the target for injection. A mixture of clay and cement was injected into the boreholes in four phases. Displacement was measured at control points after each phase, and calculations were used to determine the volume of grout that should be injected at different locations during the next phase to create uniform displacements. The observed uplift was greatest in the centre of the area after the first phase of injections, but became progressively more uniform, and displacements appear to be within 20 per cent of 10 cm over all but the eastern edge of the area after the fourth phase (Gallavresi & Carbognin 1987, fig. 6). It is particularly noteworthy that the displacement of a benchmark was measured at 9.6 cm during the experiment (figure 5d) and subsided only approximately 1 cm over the next 11 years (figure 5; Gallavresi & Carbognin 1987, fig. 12). In addition, the test area included two small old buildings (figure 5d) in poor structural condition that sustained the experiment.

The Poveglia experiment demonstrates that multiple grout injections can be controlled to create significant, uniform and long-lasting displacements at the ground surface. The experiment is similar to the SIRGE approach since a grout mix was injected at a pre-established depth to cause a horizontal rupture of the soil with a resulting formation of a new layer (figure 5b). The borehole spacing may have been closer than necessary for hydraulic fracturing, but the experiment shows that multiple injections at the same location can result in the consequent homogeneous lifting of the overlying ground.

A related experiment was conducted in Whitehouse, FL, to evaluate the feasibility of creating a layer of clay that could prevent the downward flow of contaminants (Brunsing 1987). The Whitehouse experiment injected clay slurry into boreholes spaced roughly 5 m apart and completed at a depth of 8 m over an area of 18 m on a side. The approach was to first create hydraulic fractures between the boreholes and then inject clay to dilate the fractures and lift the ground surface. The result was a roughly continuous layer of clay approximately 30 cm thick with corresponding displacements at the ground surface.

The Poveglia experiment was based on compensation grouting, a process of multiple grout injections into a designated zone (e.g. Soga et al. 2004). Today, compensation (or fracture) grouting is routinely used to offset local subsidence and to raise buildings safely—including Big Ben (Haimoni & Wright 1999)—by injecting solids beneath them (Hausmann 1990). Since the SIRGE process would be conducted deeper, using larger volumes of solids than current applications of compensation grouting, the control on small-scale displacements may be reduced. In such cases, compensation grouting could be a companion to SIRGE because it is based on the same physical phenomenon (hydraulic fracturing of soft sedimentary formations) and allows fine-scale modification of displacement gradients.

Field tests of grout injection into hydraulic fractures were also conducted at Oak Ridge, TN, where the surface displacement was measured to estimate the form of the fracture at depth (Sun 1969). These tests were much deeper than most applications of compensation grouting because they were designed to evaluate the feasibility of adding waste materials to the grout and disposing of...
the mixture by injecting it into hydraulic fractures. One representative example consists of injecting 346 m$^3$ of grout into shale at a depth of 285 m (Sun 1969). The results show that injection produced dome-like displacements spread over a region of roughly 500 m across and with a maximum amplitude of 12 mm (electronic supplementary material, figure B2). Grout was observed in cores from rock underlying the maximum uplift. This example demonstrates the feasibility of uplifting the ground surface using hydraulic fractures at depth and length scales of hundreds of metres.

Field experiments at the Munmorah State coal mine in Australia have demonstrated the feasibility of creating hydraulic fractures to lift the ground surface and offset subsidence caused by underground mining (Jeffrey et al. 1993). A hydraulic fracture was propagated at a depth of 24 m and filled with 3850 kg of sand, which created a feature approximately 30 m in radius (Jeffrey et al. 1993; Jeffrey & Settari 2000). Field monitoring indicated that the fracture was propped open by 3–5 mm of sand, and surveying indicated 4 mm of uplift at the ground surface (Jeffrey et al. 1993).

Finally, horizontal hydraulic fractures have also been registered in shallow petroleum formations. For example, Britt et al. (2007) created horizontal fractures in sandstone (Western Missouri) at depths ranging from 40 to 70 m. Using tilt meters, they determined fracture sizes of approximately 90 m.

(c) Geological examples

The SIRGE process differs from the existing engineering operations largely in the scale of the application. The Whitehouse and Poveglia tests involved injected volumes of the order of 10–10$^2$ m$^3$, and the Oak Ridge test involved slightly greater volume. In contrast, lifting 1 km$^2$ by 1 m would require injecting approximately 10$^6$ m$^3$. Hydraulic fractures are created in the petroleum industry with $\sim$10$^3$ m$^3$ of sand (Economides & Nolte 2000), but even this application is considerably smaller than required for the SIRGE process.

It is possible that there are scale-dependent effects that could cause solid injections at large sizes to differ significantly from the injections observed in engineering applications. To address this issue, we turn to sand sills, or sand injectites (e.g. Shoulders & Cartwright 2004). Sand injectites range in thickness from less than a metre to several tens of metres and extend laterally from hundreds of metres to a kilometre or more (figure 6a). In the Faeroe–Shetland basin, for example, these features are 500–1000 m in diameter and up to 20–30 m thick (Shoulders & Cartwright 2004). Detailed interpretation of seismic data indicates that these bodies were formed at depths of 200–300 m below the sea floor and lifted their overburden when they were emplaced (Shoulders & Cartwright 2004). Similar features are observed in seismic data from the North Sea, where they are tens of metres thick and more than 1 km in diameter (Huuse & Mickelson 2004). The intersection of some of these features by wells confirms that they are sand layers and not of igneous origin.

Sand injectites are widespread geological examples of the mobilization and injection of sand into sediments at depths of less than a few hundred metres. These features involve sand volumes of the order of 10$^6$ m$^3$ or larger emplaced as a sequence of injections. In form, the sand injectites resemble environmental...
Injectites indicate that sand has been injected in nature at the scales and geometries of the SIRGE process. It is certainly possible that the formation of sand injectites involves processes, such as fluidization caused by seismicity (Shoulders & Cartwright 2004), which would be difficult to duplicate in an engineering setting. Nevertheless, the similarity between the forms of engineered hydraulic fractures and sand injectites suggests that the scale difference between these features may not necessarily introduce fundamentally different mechanisms.

5. SIRGE fractures

Hydraulic fractures are widely created at significant depth in petroleum reservoirs and at shallow depth in contaminated materials, but less experience exists at intermediate depths of 30–300 m and in materials expected for the SIRGE process. Therefore, it will be worthwhile to discuss the expected parameters and regimes of propagation of SIRGE fractures.

(a) Parameters

We conceptualize the fractures created during the SIRGE process as circular planar, singular, features propagating owing to the injection of a viscous, Newtonian fluid into a wellbore at their axes (figure 1a,b). Propagation is assumed to initiate when the fluid pressure exceeds a critical value related to properties of the formation, geometry of the borehole, characteristics of injected fluid and other factors. Many un lithified sediments are likely to have at least some cohesion caused by partial saturation or cementation (figure 2).
Here, we consider fracture propagation in a formation that can be characterized by fracture toughness, although hydraulic fracture growth in soft formations may include other mechanisms (§4a). We first assume that the fluid leak-off from the propagating fracture is insignificant.

Hydraulic fracturing represents a special case in fracture mechanics that includes coupling between elastic deformation, energy dissipation in solid near the fracture tip, viscous fluid flowing in the fracture and leaking off into the solid, fluid lagging behind the fracture tip and other processes. The coupling effects have been described by Spence & Sharp (1985), Lister (1990), Desroches et al. (1994), Detournay (2004), Adachi et al. (2007), Mitchell et al. (2007) and Garagash (2009) among others. It appears that processes taking place near the fracture front and the corresponding scales control the response of the entire fracture. Also, fracture propagation regimes can be characterized by the energy required to create new fracture surfaces (to overcome fracture toughness) and the energy dissipated in viscous flow along the fracture.

Viscous dissipation in a circular fracture can be particularly important early in the growth history when a small aperture results in large viscous friction during fluid flow. At this stage, the resistance to fracture growth caused by the fracture toughness of solid material would be insignificant when compared with that due to viscous losses, and the fracture propagates in the viscosity-dominated regime. The importance of viscous dissipation decreases with time, however, as the fracture widens and as the fluid velocity decreases (in radial fractures). When the fracture becomes sufficiently large, the propagation resistance owing to the viscous losses becomes much smaller than resistance of solid material to fracture. At this stage, the fracture grows in the toughness-dominated regime and the fluid pressure in the fracture is essentially uniform (Savitski & Detournay 2002). The viscosity-dominated and toughness-dominated regimes occur when $t \ll t_m$ and $t \gg t_m$, respectively (Detournay 2004; Bunger & Detournay 2007), where $t$ is the injection (propagation) time and

$$t_m = \left( \frac{\mu' Q^3 E'^{13}}{K'^{18}} \right)^{1/2},$$

with $\mu' = 12\mu$, $E' = E/(1 - \nu^2)$, $K' = 4(2/\pi)^{1/2}K_{IC}$, $\mu$ is the viscosity of injected fluid, $K_{IC}$ is the fracture toughness of the formation and $Q$ is the injection rate.

In cohesive materials, the injected fluid lags behind the tip of a fracture (e.g. figure 4a). This process may affect fracture propagation unless the lag size is negligible when compared with the fracture size, $\ell$. In the case of no leak-off, the largest fluid lag develops when $K_{IC} = 0$ (Garagash & Detournay 2000), and the distance from the crack tip over which the effect of lag vanishes scales as $L_\mu = \mu' E^2 V/(\sigma_0 - p_1)^3$ (Garagash 2009), where $\sigma_0$ is the confining stress closing the fracture ($\sigma_0 \approx \rho gh$ for SIRGE applications), $p_1$ is the pressure in the lag and $V$ is the crack growth velocity. Parameter $L_\mu$ scales with the lag size (Garagash & Detournay 2000), and the characteristic time $t_0$, during which the fracture tip advances a certain distance of the order of the lag size, is

$$t_0 = \frac{E^2 \mu'}{(\sigma_0 - p_1)^3}.$$
This follows from $L_\mu \sim V t_0$, and, because $\ell \sim V t$, condition $L_\mu \ll \ell$ can be expressed as $t \gg t_0$. Therefore, the effect of lag on fracture propagation can be neglected when $t \gg t_0$. Expression (5.2) was obtained by Buenger & Detournay (2007) for penny-shaped fractures, although $L_\mu$ appears to be a universal length scale that is independent of the fracture geometry and fluid injection conditions (Garagash 2009).

Time scales $t_0$ and $t_m$ typical for radial hydraulic fractures in petroleum reservoirs have been evaluated by Buenger & Detournay (2007), but formation properties ($E'$ and $K_{Ic}$, in particular) and the in situ stress encountered in SIRGE applications are likely to differ from petroleum reservoirs. To estimate $t_0$ and $t_m$ for SIRGE injections, we estimate that the pumping rate, $Q$, will probably be in the range of $\sim 10^2$–$10^3$ m$^3$ d$^{-1}$, the injection time $t$ is expected to range from hours to days, and $E'$ will range from 10 to 10$^3$ MPa. We also anticipate that net confining stress $\sigma_0 - p_1$ will be at least 0.5 MPa (which corresponds to a depth of $h \approx 25$ m and insignificant fluid pressure in the lag zone). Viscosities of water-based slurry can span a broad range from slightly greater than 1 cP to 1000 cP or more (Abulnaga 2002), depending on the composition and content of solids (see also §3b). Hence, the expected range of viscosities is $\sim 10$–$10^3$ cP.

Fracture toughness of soft, un lithified formations, $K_{Ic}$, is probably the most uncertain parameter. Laboratory experiments suggest that it ranges from $\sim 0.1$ MPa $\times$ m$^{1/2}$ for partially saturated particulate materials to $\sim 0.01$ MPa $\times$ m$^{1/2}$ for fully saturated materials (Murdoch 1993; Harison et al. 1994; Wang et al. 2007; Zhang et al. 2008). Experiments with cohesionless particulate materials (Chang 2004) indicate that their apparent fracture toughness can be $\sim 1$ MPa $\times$ m$^{1/2}$, which is similar to the $K_{Ic}$ of many rocks (e.g. Atkinson & Meredith 1987). Although a sound mechanical model of fracture growth in cohesionless materials is not yet available (as reviewed in §4), using $K_{Ic}$ can be understood as characterizing the energy necessary for creating the fracture and the corresponding scale at the fracture tip.

It has been reported that $K_{Ic}$ increases with fracture scale in rock materials, and can be as great as approximately 10 MPa $\times$ m$^{1/2}$ (e.g. Shlyapobersky et al. 1988; Dyskin & Germanovich 1993), suggesting that laboratory values may underestimate values of $K_{Ic}$ in the field. To our knowledge, only one study (Murdoch 2002) is available where estimates of $K_{Ic}$ in un lithified formations were determined for propagating hydraulic fractures in the field. By considering fluid flow in the fracture with negligible pressure change owing to viscous losses—a scenario consistent with the toughness-dominated regime—Murdoch (2002) obtained $K_{Ic} \sim 0.1$ MPa $\times$ m$^{1/2}$ for silty clay. These data led us to assume that $K_{Ic} \sim 0.1$–$1$ MPa $\times$ m$^{1/2}$ for SIRGE fractures in un lithified formations, although additional investigations are needed to improve this range.

Time scale $t_0$ is expected to be less than $\sim 10$ s for the range of parameters outlined above, according to equation (5.2). Injection times $t$ are expected to be much greater than 10 s, so $t \gg t_0$, and it appears to be reasonable to ignore the effects of fluid lag when estimating fracture characteristics. Time scale $t_m$ can span a broad range, however, from less than a millisecond to more than a year, depending on the parameters. In particular, $t_m \sim 10^{-4}$ s, in the example given in §3, so those fractures would propagate mostly in the toughness-dominated regime. For the field conditions analysed by Murdoch (2002) ($K_{Ic} \sim 0.1$ MPa $\times$ m$^{1/2}$ and $E' \sim 10$–$10^2$ MPa), $t_m$ is less than 10 min even for the largest expected values of $Q$. 

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and $\mu$ ($\sim 10^3$ m$^3$ d$^{-1}$ and $\sim 10^3$ cP, respectively). This also indicates that the growth of SIRGE fractures for these parameters will typically be toughness-dominated ($t \gg 10$ min).

Lithification is likely to stiffen the formation and increase $t_m$ by increasing $E'$. For example, $t_m$ ranges from less than a day to more than a year, when $E' = 10^3$ MPa, $Q = 10^2$ m$^3$ d$^{-1}$, $K_{lc} \sim 0.1$ MPa $\times$ m$^{1/2}$ and $\mu = 10^2$–$10^3$ cP, so the propagation regime would be viscosity-dominated, when $t \ll t_m$. On the other hand, lithification may also increase $K_{lc}$. For example, increasing $K_{lc}$ to 1 MPa $\times$ m$^{1/2}$ reduces $t_m$ to less than a second for the entire discussed range of parameters and fracture propagation becomes toughness-dominated. Overall, we find that SIRGE fractures can be either toughness- or viscosity-dominated, but most applications in relatively soft sedimentary formations are expected to be toughness-dominated. The exception is for the injection of sufficiently viscous fluids ($\mu \sim 10^2$–$10^3$ cP) into relatively weak ($K_{lc} \sim 0.1$ MPa $\times$ m$^{1/2}$), yet stiff ($E' \sim 10^3$ MPa or greater), formations.

For comparison, $t_0$ will usually be less than a second and $t_m$ is expected to be greater than a day for hydraulic fractures created under conditions typical of petroleum reservoirs (Bunger & Detournay 2007). This suggests that fluid lag is negligible, but, in contrast to SIRGE, fractures in petroleum reservoirs typically grow in the viscosity-dominated regime. The difference in propagation regimes occurs because the modulus, $E'$, in petroleum reservoirs is generally greater, while the injection time, $t$, in petroleum applications is smaller, than expected for SIRGE applications.

(b) Fracture size, aperture and pressure

Numerical simulations are required to estimate the expected characteristics of hydraulic fractures created during the SIRGE process in general (e.g. Murdoch & Germanovich 2006; Adachi et al. 2007), but closed-form solutions are available to characterize special cases. For example, because we can ignore the effects of fluid lag, the basic fracture characteristics of penny-shaped fractures with no leak-off can be represented as (Savitski & Detournay 2002)

$$\begin{align*}
\omega &= \varepsilon(t) L(t) \Omega(\rho, t), \\
p &= \varepsilon(t) E' \Pi(\rho, t) \\
a(t) &= \gamma L(t),
\end{align*}
$$

where $\rho = r/a$, $r$ and $t$ are the radial coordinate and injection time, respectively, $\omega(r, t)$ is the fracture aperture, $a(t)$ is the fracture radius and $p(r, t)$ is the net pressure (difference between fluid pressure, $p_f$, and confining stress, $\sigma_0$). In the viscosity-dominated regime ($t \ll t_m$),

\[\varepsilon(t) = \left(\frac{\mu'}{E'} t\right)^{1/3}, \quad L(t) = \left(\frac{E' Q^3 t^4}{\mu'}\right)^{1/9}, \quad \gamma \approx 0.6955, \quad \Omega(\rho) = \gamma(t) \Omega_*(\rho)\]

\[\Omega_*(\rho) = [C_1 - C_2(6 - 13\rho)](1 - \rho)^{2/3} + \frac{8}{\pi} B \left[(1 - \rho^2)^{1/2} - \rho \arccos \rho\right]\]

and

\[\Pi(\rho) = B_0 - \frac{2}{3} B_1 (1 - \rho)^{-1/3} - B \ln \left(\frac{\rho}{2}\right),\]

(5.4)
whereas in the toughness-dominated regime ($t \gg t_m$)

$$
\varepsilon(t) = \left( \frac{K^6}{E^6 Q t} \right)^{1/5}, \quad L(t) = \left( \frac{E^2 Q^2 t^2}{K'} \right)^{1/5}, \quad \gamma = \left( \frac{3}{\pi \sqrt{2}} \right)^{2/5}
$$

$$
\Omega(\rho) = \left( \frac{3}{8\pi} \right)^{1/5} (1 - \rho^2)^{1/2}
$$

and

$$
\Pi(\rho, t) = \left( \frac{\pi}{8} \right) \left( \frac{\pi}{12} \right)^{1/5} + \left\{ A_1 - A_2 \left[ \frac{1}{3} \ln \rho - \frac{1}{5} \ln(1 - \rho^2) \right] \right\} M(t),
$$

where $C_1 \approx 1.909$, $C_2 \approx 0.07054$, $B_0 \approx 0.7950$, $B_1 \approx 0.3581$, $B \approx 0.09269$, $A_1 \approx 0.6380$, $A_2 \approx 1.709$, and the dimensionless fluid viscosity $M(t) = (t/t_m)^{-2/5}$.

When $M = 0$, equation (5.5) reduces (Detournay 2004) to the zero-viscosity solution of Abe et al. (1976). Although $M$ is small in equation (5.5), we kept the first-order term in $\Pi$ (but not in $\Omega$ or $\gamma$) to emphasize that the pressure distribution has singularities at the fracture front and near the injection point (Savitski & Detournay 2002). In reality, these singularities do not appear because of the fluid lag and the finite size of the injection borehole, but including the first-order term takes into account that fluid pressure in the fracture may be somewhat elevated near the borehole. This effect appears to be insignificant for the chosen range of SIRGE parameters (§5a).

The parameters used for the example in §3 ($E = 100$ MPa, $\nu = 0.35$, $K_{lc} = 0.2$ MPa $\times$ m$^{1/2}$, $\mu = 10^2$ cP, $Q = 200$ m$^3$ d$^{-1}$) give a radius of $a = 55$ m and an average aperture of 2 cm, where equation (5.5) is used in equation (5.3), because $t_m \sim 10^{-4}$ s and the propagation regime is toughness-dominated. These parameters further serve as a baseline for the SIRGE example. Increasing Young’s modulus to $E = 10^3$ MPa and viscosity of the slurry to $\mu = 10^3$ cP increases $t_m$ to approximately 3 days (equation (5.1)), which causes propagation to become viscosity-dominated. This will approximately double the fracture radius (to $a \approx 110$ m) and halve the average aperture (to 0.75 cm), according to equations (5.3) and (5.4). This range of fracture radius ($a \sim 50–100$ m) may be large enough to cause the fracture to interact with the ground surface, an effect that may change fracture characteristics when compared with calculations that assume an infinite region (e.g. equations (5.4) and (5.5)). Because the fractures are still relatively short ($a/h \sim 1$), the effect of interaction can be taken into account in the far-field approximation by adding to the net pressure, $p$, an extra term $p' \sim (a^2/h^2) p$ (Dyskin et al. 2000) and without changing the fracture (aperture) shape. Since $a/h \sim 1$, this additional pressure is, at most, of the same order as that of a fracture in the infinite space (equations (5.4) and (5.5)), and we expect that the effect of fracture–ground surface interaction on fracture dimensions will be relatively minor. If the fracture becomes larger ($a/h \gg 1$), then the fracture–surface interaction will change the fracture aperture and affect functions $\Omega$ and $\Pi$ in equations (5.4) and (5.5) (Bunger & Detournay 2005).

Furthermore, strong interaction with the ground surface curves the fracture upward (e.g. Murdoch 1995; Germanovich & Dyskin 2000; Buner et al. 2008), increasing the risk of slurry venting to the surface—particularly when the stress ratio is only slightly greater than 1. Fractures curved and intersected a free surface when their radius was approximately three times their initial depth ($a/h \approx 3$) in

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field tests in sediments (Murdoch 1995; Murdoch et al. 2006) and in laboratory
tests in transparent plastic (Bunger et al. 2008). Therefore, it appears that
maintaining $a/h \approx 1$ should limit the risk of fractures reaching the ground surface
as a result of mechanical interactions with the surface.

(c) Leak-off

Hydraulic fractures are affected by fluid flowing out through their walls, or leak-
off (Lenoach 1995; Burger et al. 2005; Mitchell et al. 2007; Adachi & Detournay
2008). To develop a basic understanding of the effect of leak-off in SIRGE
applications, we employ Carter’s leak-off coefficient (Economides & Nolte 2000),
$C_L$, in the analysis of the toughness-dominated growth of a penny-shaped fracture
with negligible lag in a permeable medium (Bunger et al. 2005). For this case,
the terms in equation (5.3) are

$$
\varepsilon = \left(\frac{C^2 K^2}{E^2 Q}\right)^{1/3}, \quad L = \left(\frac{K' Q}{E' C^2}\right)^{2/3}, \quad \gamma = \left(\frac{t}{t_L}\right)^{2/3} \sum_{n=0}^{4} C_n \left(\frac{t}{t_L}\right)^{n\beta}
$$

(5.6)

$$
\Omega(p, t) = 2^{-1/2}\gamma^{1/2}(1 - p^2)^{1/2}, \quad \Pi(p, t) = \frac{\pi}{2}2^{-5/2}\gamma^{-1/2}
$$

where $t_L = (K'/Q)^{2/3}(E'/C^2)^{-2/3}$, $C' = 2C_L$, and the dimensionless fracture size $\gamma$
can be represented by the direct match of the asymptotic solutions for small
and large times (Bunger et al. 2005). When $t/t_L \leq \delta$, $\delta = 2/5$, $\beta = 3/10$ and
$C_0 = 0.8546$, $C_1 = -1.110$, $C_2 = 1.562$, $C_3 = -1.772$, $C_4 = 1.337$. When $t/t_L > \tau$,
$\delta = 1/4$, $\beta = -3/8$ and $C_0 = 0.4502$, $C_1 = -3.824 \times 10^{-2}$, $C_2 = 4.685 \times 10^{-3}$, $C_3 = -3.322 \times 10^{-4}$, $C_4 = 0$. Leak-off is insignificant when $t \ll t_L$, whereas it is an
important process when $t \gg t_L$ (Bunger et al. 2005). The matching is nearly
exact for $0.01 < \tau < 0.1$ and any $\tau$ from this interval (say, $\tau = 0.05$) can be chosen
for practical calculations. For small times, expressions (5.5) and (5.6) become
equivalent in the leading term ($M = 0$ and $t \ll t_L$). Expressions (5.6) can be used
if $t_m \ll t_L$. To our knowledge, no close-form solution is currently available for
a circular fracture if this condition is not satisfied, and the problem should be
solved numerically. Therefore, to compare the toughness- and viscosity-dominated
regimes with leak-off, we used the existing solutions (Bunger et al. 2005; Adachi &
Detournay 2008) for the plane-strain propagation of a hydraulic fracture in a
permeable rock.

Carter’s coefficient can be estimated using the small-time asymptotic solution
of the one-dimensional pressure diffusion problem for a half-space when ideal
conditions, such as no filter cake and a small infiltrated zone, can be assumed.
This results in an upper estimate of the leak-off coefficient $C_L \approx \delta p(k/\mu)(\pi D)^{-1/2}$
(Economides & Nolte 2000), where $\delta p = p_t - p_0$ is the hydraulic load (assumed
approximately constant), $p_0$ is the pore pressure in the sediment, $p_t$ is the fluid
pressure in the fracture, $k$ is the formation permeability and $D$ is the hydraulic
diffusivity of the formation.

As an illustration, we use the example considered in §3. First, we assume
that the underlying material is silt, which is typical of New Orleans (Kolb &
Saucier 1982) and Venice (Comerlati et al. 2004; Simonini et al. 2007). Using
parameters from Freeze & Cherry (1979) gives $k/(\pi D)^{1/2} \sim 10^{-13}\text{m/\s}$. When the

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fluid pressure in the fracture is similar to the overburden stress \((p_i \approx \sigma_0)\) and the pore pressure is relatively small \((\sigma_0 \gg p_0)\). \(\delta p\) can, indeed, be considered constant. We then find \(C_L \approx 2.2 \times 10^{-4} \text{ cm s}^{-1/2}\), and \(t_L \approx 10^{10} \text{ s}\). Therefore, the effect of leak-off on fracture propagation is negligible in this example because \(t \ll t_L\). The effect of a lag zone can also be ignored because \(t_m \approx 2.3 \times 10^{-4} \text{ s}\) and \(t \gg t_m\) for most of the injection period. Finally, the approximation of the toughness-dominated regime can be used because \(t_m \ll t_L\) in this case.

The importance of leak-off can be illustrated by assuming next that the fracture is in the sand rather than in the silt, which would increase \(k/(\pi D)^{1/2}\) to approximately \(10^{-11} \text{ m s}^{-1}\) (Freeze & Cherry 1979). This changes \(t_L\) to approximately 50 min, so most of the time the fracture would propagate in the leak-off-dominated regime. The toughness-dominated character of the propagation is unaffected, so equation (5.6) is still applicable. The leak-off coefficient increases to \(C_L \approx 2.2 \times 10^{-2} \text{ cm s}^{-1/2}\). This causes the radius of the fracture to reduce from \(a = 55 \text{ m}\) for the baseline to only 17 m, while the average fracture aperture is reduced from 2 cm to 1.1 cm, according to equation (5.6).

This analysis shows that leak-off will reduce the length and thickness of a fracture, but the results given above are an upper estimate of this effect. We assumed that the injected slurry (sediment) itself can leak off, whereas, in reality, only fine-grained particles will be able to migrate from the slurry into the formation. In addition, the pore pressure will increase with repeated injections and this will decrease the leak-off rate. We conclude that leak-off into fine-grained formations, such as silt or clay, will probably be minor, whereas the effects of leak-off when fractures are created in sands may reduce the fracture dimensions.

Leak-off after propagation drains water from the fractures. The same model used to analyse leak-off during propagation can be used to estimate leak-off after the fracture stops growing. The leak-off flux is \(q = C_L/t^{1/2}\) through one fracture wall. Hence, the time required for the fracture to close by a fractional amount \(\chi\) can be estimated as \(t_d = (\chi w_0)^2/(4C_L)^2\), where \(w_0\) is the average fracture aperture at the end of propagation. We use \(w_0 = 2 \text{ cm}\) (§3), \(\mu \approx 1 \text{ cP}\) and set \(\chi \approx 0.5\), which will allow the fracture walls to be supported by injected solids, when the solids ratio in the injected slurry is 30 per cent by volume (§3). Furthermore, we assume that the pore pressure has been significantly elevated by repeated injection and leak-off. For example, let \(p_i \approx 0.98 \sigma_0\), \(p_f \approx \sigma_0\), which results in a small hydraulic load \(\delta p\) driving leak-off. Under these conservative conditions, we obtain that \(t_d \approx 4\) days, which is smaller than the time of 10 days between injections in the example described in §3. We simplified the analysis by assuming that the fluid leaking off during propagation is the clay-rich slurry (\(\mu = 100 \text{ cP}\)), while between injections the solid particles and water separate and the water leaks off (\(\mu = 1 \text{ cP}\)). These results demonstrate that leak-off may have only a minor effect on propagation under the conditions of the SIRGE example assumed in §3, but it can be large enough to significantly drain the water out of a fracture between SIRGE injections.

We recognize that many factors not included here may be important and cause fracture characteristics to differ from those given by equations (5.3) to (5.6). For example, complex nonlinear behaviour of particular materials, interaction between densely packed fractures (e.g. Germanovich et al. 1994; Germanovich & Astakhov 2004), effects of leak-off on changing slurry composition and rheology (Abulnaga 2002), channelling of flow in the fracture...
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(Murdoch et al. 2006; Wu et al. 2007), filter cake formation (Economides & Nolte 2000) and coupling between fracture segmentation and preferential flow of proppant (Murdoch et al. 2006), among other effects, are not represented in the analyses we used. Nevertheless, the analyses outlined above represent fundamental physical processes and suggest that hydraulic fractures with characteristics needed for SIRGE could be created.

6. Discussion

The merits of the Galveston Grade Raising inspired proposals to implement this approach in New Orleans (Petroski 2006). The Galveston-style grade raising, however, may cause significant inconvenience to residents (e.g. figure A1, see electronic supplementary material; Frank 2003). Moreover, it is probably impractical to raise some buildings using jacks, and raising buried infrastructure is likely to create additional complications. It seems that the SIRGE method has the potential to raise elevations with considerably fewer problems. By injecting solid materials at depths of the order of 100 m or more, it should be feasible to cause uplift with relatively small horizontal displacement gradients. Material would be injected below the lowest footing or foundation, so the overburden would be displaced as a continuous slab. This would limit the impact on existing buildings or infrastructure.

(a) Hydraulic fractures beneath New Orleans

The main uncertainty in successfully implementing the SIRGE process is the geometry of hydraulic fractures. Fractures oriented from horizontal to vertical have been created in field tests (Murdoch & Slack 2002), but fractures with shallow dips will be most effective for SIRGE. The closest shallow hydraulic fracturing project to New Orleans to our knowledge is an effort conducted in alluvial silt, clay and fine-grained sand in the floodplain of the Sabine River (site no. 10, fig. 3 in Murdoch & Slack 2002). Hydraulic fractures created at depths between 8 and 15 m were nearly horizontal, and they caused surface displacements of roughly 1 cm each. Fractures at the Sabine site were located using borings, and their form, resembling figure 2, would be suitable for ground-lifting.

The geology of New Orleans consists of Mississippi River delta deposits underlain by Pleistocene sedimentary deposits at depths of 25–35 m (Kolb & Saucier 1982). The delta deposits are soft clays and silts with interbedded fine-grained sands, much like the site at the Sabine River. The underlying deposits are relatively stiff clays, silts and sands that went through many wetting–drying cycles when the region was high above sea level during the Pleistocene (Kolb & Saucier 1982). In our experience (Murdoch & Slack 2002), hydraulic fractures are typically gently dipping (e.g. electronic supplementary material, figure B1) in materials that have been exposed to many wetting–drying cycles, presumably because these cycles increase horizontal compression.

(b) Poroelastic preconditioning

Despite the optimism about the ability to create favourably oriented hydraulic fractures, ambient stresses at some locations will cause hydraulic fractures to be steeply dipping and of limited value to the SIRGE process. One way
to extend the applicability of SIRGE is to develop a way to alter \textit{in situ} stresses to make the fracture orientation more favourable. It is well known that manipulations of subsurface fluids during waste disposal or petroleum recovery can significantly change \textit{in situ} stresses due to the poroelastic effect (e.g. Segall \textit{et al.} 1994; Germanovich & Chanpura 2001). This has caused problems, by reactivating faults and inducing seismicity (Healy \textit{et al.} 1968; Segall \textit{et al.} 1994; Germanovich & Chanpura 2006), yet the same principle could be beneficial to the SIRGE process.

As an example, assume that we gradually pressurize the aquifer for the purpose of preconditioning the stresses before injecting the slurry as a part of the main SIRGE procedure. To evaluate this process, consider an infinite, horizontal, poroelastic layer, $-h < z < 0$, in an elastic half-space $z < H$ (figure 6b). For simplicity, assume that the pressure within the layer is changed everywhere by the same amount of $\Delta p > 0$, while outside the layer the pore pressure remains the same:

$$\Delta p = \begin{cases} 0 & (z < -h, \ 0 < z < H), \\ \Delta p & (-h < z < 0). \end{cases}$$

The stress increments caused by this pressure change satisfy the uniaxial strain constitutive relations (e.g. Wang 2000)

$$\Delta \sigma_{zz} = \frac{2G(1-\nu)}{1-2\nu} \varepsilon_{zz} - \alpha \Delta p, \quad \varepsilon_{zz} = \partial w/\partial z$$

and

$$\Delta \sigma_{yy} = \Delta \sigma_{xx} = \frac{\nu}{1-2\nu} \Delta \sigma_{zz} - 2\eta \Delta p, \quad \eta = \frac{\alpha(1-2\nu)}{2(1-\nu)}. \quad (6.2)$$

The boundary condition on the half-space surface is $\Delta \sigma_{zz} = 0$ ($z = H$). Because $\partial(\Delta \sigma_{zz})/\partial z = 0$ (equilibrium condition), the vertical stress increment equals zero everywhere in the half-space: $\Delta \sigma_{zz} = 0$ ($z < H$). Therefore, integrating $\varepsilon_{zz}$ gives (1.1), and expression (6.2) results in horizontal stress increments

$$\Delta \sigma_{yy} = \Delta \sigma_{xx} = \begin{cases} 0 & (z < -h, \ 0 < z < H), \\ -2\eta \Delta p & (-h < z < 0), \end{cases}$$

which are negative (compressive) inside the layer to be treated (because $\eta > 0$). Assuming that $\alpha \approx 1$ and $\nu \approx 1/3$ (typical for soft sedimentary deposits and surficial materials), we see that $2\eta \approx 0.5$. That is, the increments of horizontal compressive stress scale as half the pressure increase in the pressurized layer.

The considered poroelastic effect relies on a one-dimensional approximation, which may be violated during the transitory phases. Nevertheless, equation (6.3) shows that raising the pore pressure increases the ratio of horizontal to vertical compression, thereby suppressing vertical and promoting horizontal hydraulic fractures. This provides a technique to manipulate stresses to increase the effectiveness of SIRGE. This also suggests that increases in pore pressure as a result of fluid leak-off following hydraulic fracturing may help in promoting horizontal orientations of subsequent fractures.

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Raising elevations in New Orleans is by no means the only potential application for the SIRGE process. The Poveglia experiment (Marchini & Tomliolo 1977; Gallavresi & Carbognin 1987) demonstrated that the ground elevation in the vicinity of Venice could be raised permanently by injecting solids, but a city-wide scale-up would be required. The sea water injection method proposed to raise Venice (Comerlati et al. 2004; Castelletto et al. 2008) provides the necessary scale-up to the size of the city, but requires ongoing pumping to maintain fluid pressures to sustain uplift. The Rialto proposal (BAMS 2008; Sandri 2008) to use hydraulic jacks for raising individual buildings could provide permanent uplift, but it could be logistically cumbersome when compared with the subsurface sea water injection. The SIRGE method appears to be a reasonable compromise. It would offer the potential for permanent uplift provided by the Poveglia experiment and the use of hydraulic jacks with the scale advantages of the sea water injection proposal. The logistics of implementing the SIRGE process could be considerable, but we expect them to be significantly less disruptive than raising each building using jacks.

The long list of endangered locations also includes Shanghai and New York, but there are many smaller areas, such as the MOSE gates and Kansai airport, where the SIRGE process has the potential to reduce flood risks. The MOSE project (e.g. Nosengo 2003) would create a row of gates that would be raised temporarily to block the inflow of sea water through entry points into the Venice lagoon. Field tests using an embankment to simulate a full-sized gate showed roughly 0.5 m of subsidence. The subsidence rate slowed with time, but was ongoing when the project ended 5 years after construction (Simonini et al. 2007, fig. 40). Subsidence of the MOSE gates is of considerable concern because it could cause premature failure long before the design life of 100 years is realized. A large effort is underway to adequately design the foundations of the MOSE gates (Simonini et al. 2007), but, because of the 100 year design life, there could be considerable uncertainty in forecasting the differential settlement. The SIRGE technique could be used to lift areas where differential subsidence could be larger than expected, providing an additional factor of safety to the MOSE project. Similarly, the SIRGE method could be used to elevate the subsiding levee system in New Orleans (Dixon et al. 2006).

7. Conclusion

A reliable way to protect coastal cities from catastrophic flooding is to elevate them above surging water levels, as demonstrated by the success of the Galveston Grade Raising project implemented a century ago. A modern version of grade raising could be based on injecting sediment into the subsurface at shallow depths, where it would spread laterally by a process resembling hydraulic fracturing (or compensation grouting). The injection process would be repeated at adjacent locations to create a network of sub-horizontal, overlapping injections causing ground surface displacement similar to the thickness of solid material injected at depth. Analysis of hydraulic fracturing in soft, shallow formations suggests that the process could be implemented to lift ground elevations by roughly 1 mm d$^{-1}$.

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resulting in 1 m of uplift in 3 years and 10 m in 30 years. The analysis also suggests that SIRGE hydraulic fractures in such formations, in contrast to petroleum reservoirs, would typically grow in the toughness-dominated regime.

Pilot tests in Italy and Florida have demonstrated the feasibility of raising elevations by multiple injections of solids into boreholes spaced every 2–5 m over areas of ∼10²–10³ m². A key to scaling this process up is to inject solids as hydraulic fractures, which spread laterally as broad, flat sheets and would allow spacing of wells to be increased. Examples of hydraulic fractures at depths of up to tens of metres that lift the ground surface are available from environmental and geotechnical applications. The SIRGE scale of the ground-lifting process could be several orders of magnitude larger, but geological examples exist where natural processes have injected sand into sedimentary deposits to form layers of ∼1–10 m thick and ∼1 km or more in lateral dimension. Therefore, it seems feasible that the process of solid injection can be scaled up from current applications to a viable technique for reducing the risks of catastrophic flooding in coastal areas with suitable in situ stresses.

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