Waste Disposal Monitoring Using Surface Displacement Field

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ABSTRACT: Massive injection of slurried solid waste generates permanent strains and displacements. These can be measured and analyzed to give useful information related to the shape and orientation of the injected body, and therefore lead to a monitoring approach based on accurate surface measurements of vertical movements or tilt. We discuss waste emplacement, present information showing the magnitudes of the final deformations, and show how some displacement field features are sensitive to certain parameters, whereas others are insensitive. Tilt measurements continuously through time give the best possibility of accurate monitoring of the waste body.

1 INTRODUCTION

Permanent disposal of terminal solid wastes can be achieved through landfilling, ocean dumping, mine placement, injection or placement into solution caverns in salt, or by subsurface fracture injection of a slurry of water and granulated waste. The latter approach has been used for disposal of drilling wastes comprising used mud, rock chips and cavings (Willson *et al.*, 1992), as well as sand co-produced with heavy oil (Dusseault and Bilak, 1993). Slurry injection of wastes is in many ways analogous to the geological emplacement of dykes and sills (Pollard, 1987), cement slurry grouting under hydraulic structures such as dams (USDI, 1974), and hydraulic fracturing in the oil industry (Howard and Fast, 1970).

Injection of wastes requires monitoring to insure containment, to give some idea of the shape and extent of the injected body, for assessment of surface displacements, for quality control during the process, and for legal protection and regulatory control. If the orientation of the injected waste body is dominantly vertical, does it pass through strata that otherwise would serve as seals to flow? Is the solid material confined to the near wellbore vicinity, or does it travel considerable distances as a slurry before the water content drops to the point where the waste is immobilized? Whatever reasonable assumptions are made as to confinement or shape, monitoring data are required to confirm the assumptions and to collect information over the time-history of waste injection.

The injection well itself can be used for pressure build-up and decay tests, which, if the permeability and compressibility of the injected material is much different that the host rock, will yield highly averaged information about the waste zone transport properties, from which indirect deductions about orientation and shape may be possible. Special monitoring wells can be installed, but these give only punctual data, are useful only for a limited time, and for deep waste injection operations, monitoring wells are costly. Other wellbore methods such as geophysical logs or tracer tests are too local, subject to interpretative non-uniqueness, and are generally costly.

High-resolution seismic 3-D surveys, repeated and suitably analyzed, give spatial evolution of seismic wave parameters (velocities, amplitudes, attenuations). These approaches are powerful if an accurate velocity model exists, and "time-slices" from successive survey periods will show changes as the body of immobilized injected solids grows. Disadvantages are related to 3-D seismic survey costs, analysis time, interpretive models, and limited spatial resolution. Altered seismic properties must be related to the presence of the body using some assumptions, and the fact that local stresses are changing at the same time may cause interpretive difficulties. Microseismic methods using passive monitoring of emitted acoustic signals could be useful, but the technique must be further developed for systematic use as a monitoring tool for slurry waste injection. Perhaps after several field trials, these methods will become cheaper and more suitable.

Monitoring changes in the electrical potential field arising if a current drop is placed across a dipole near the waste body will be useful if the resistivity contrast is sufficiently large, and if a number of steps are taken to optimize the measurement electrode positions (Narayan *et al.*, 1993). For example, if the carrier fluid is fresh and is displacing saline water, a large contrast is possible; however, this constitutes monitoring the liquid transport, not the solid emplacement, and if low solids-content slurries are used, the latter may be a small fraction of the former.

Injection of solid wastes generates a permanent volume change in the strata at the injection point; this alters the displacement field all around the injection point, including at the surface of the earth. If it were possible to sample this displacement field with high precision as injection proceeded, it should be possible in principle to analyze those data and draw conclusions as to the waste body shape, thickness, and orientation.

In this article, we will show how slurry waste injection creates a displacement field, and how the surface component of this field can be accurately sampled and analyzed. These analyses provide a means of monitoring the process, but because a remote part of the field is being collected to infer the properties of the source, there are issues of what can be measured, how it can be analyzed, and the accuracy of the mathematically reconstructed body shape.

2 SLURRY WASTE INJECTION

Granular solid wastes can be suspended in an aqueous slurry and injected continuously into geological formations. If low permeability formations are chosen and if the wastes are fine-grained (colloidal particles), the injected fluid will travel considerable distances and the fracture will in general be of modest thickness (centimetres or less). If coarse-grained wastes are injected or if a highly permeable target stratum is selected, wastes are deposited near the wellbore, and the resultant injected body will be thick and lenticular.

At depth in most sedimentary basins, and in all extensional basins, $\sigma_3 = \sigma_{hmin}$, thus induced fractures are vertically oriented. In basins which are dominated by compressional conditions, or at shallow depths in basins which have been buried and uplifted, $\sigma_3 = \sigma_v$, and fractures will propagate in a quasi-horizontal orientation (Figure 1).

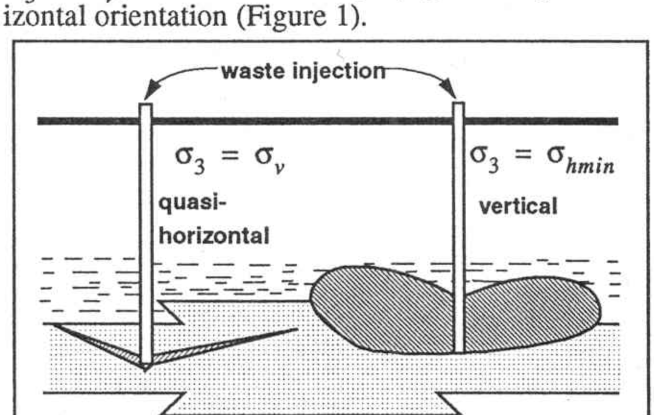

Figure 1: Stresses and Fracture Orientations

It occurs quite frequently that for shallow depths (< 1 to 2 km) massive injection will lead to a change in fracture orientation (Dusseault and Simmons, 1982) as σ_{hmin} is increased because of the stresses induced by fracture growth. Then, fractures become dominated by horizontal growth features, and the overburden is "lifted" in response to further injection. This has been observed in many steam injection operations, but of particular interest, it also happened shortly after solids injection was initiated in a trial waste disposal case. A slurry injection operation using $100\mu m$ waste sand in a waste water fluid was carried out at a depth of 690 m in Saskatchewan in a 35 m thick stratum of uncemented quartzose sand ($D_{50} \approx 150 - 500\mu m$) with a porosity of 30% and a permeability of 3-7 Darcy. The sand-water slurry was injected at pressures that rapidly became considerably larger than the total overburden stresses ($p_{inj} \sim 1.15 - 1.25\sigma_v$), reflecting the uplift of the superincumbent strata rather than parting in a vertical attitude, despite the fact that the original regional minimum stress at this depth is clearly horizontal, i.e.:$\sigma_3 = \sigma_{hmin} \approx 0.9 \cdot \sigma_v$. Apparently, the shift from vertical parting to horizontal uplift occurred within 30 minutes of initiating slurry input, and the stress alteration was permanent (as well as strains).

For horizontal fracture injection in a permeable and porous sediment, the fracture fluid bleed-off rate is very high, thus the granular solid waste is deposited near the wellbore, and plastically extruded outward by the weight of the overburden. As long as the injection pressure remains high, the formation will accept the slurry by uplift and lateral extrusion. There are no specific detailed measurements of the shape of an injected body at depth in a horizontal attitude, but arguments related to the rigidity of the overburden, plastic (frictional) extrusion, and the requirement that stresses be equilibrated suggest a lenticular shape with an aspect ratio of perhaps 10:1 in diameter over mean thickness.

For injection fractures at greater depth in regions where $\sigma_3 = \sigma_{hmin} \ll \sigma_v$, vertical fracture growth will dominate and the fracture will propagate laterally and upward. However, solids injection entails permanent strains, and the fracture growth cannot approach a "steady-state" condition where bleed-off and injection are in balance, as is the case with a liquid fracture. Thus, as long as solids are being introduced, displacements are being induced, lateral stresses will be gradually and permanently altered, and overburden uplift will eventually occur when the lateral stresses exceed the vertical stresses. It is logical to surmise that if the solids can be carried great distances before becoming immobilized, fractures will tend to be thin and long and remain vertical for an appreciable time. In rapid bleed-off cases, they will be short and fat, local lateral stresses will be affected, and alternation between vertical and horizontal growth will occur until the injected granular waste body is an appreciable fraction of the depth. When the free surface effect can be felt by the region of the strata being stressed and displaced, horizontal components will begin to dominate. In one well-instrumented case where steam rather than a slurry was used, this alternation between horizontal and vertical components was clearly observed for induced fractures at modest depth (Dusseault and Simmons, 1982).

If colloidally sized suspended wastes, slurries in viscous fluids, or slurries containing large amounts of emulsified particles (e.g.: viscous oil droplets) are injected, the pore throats of the target stratum can plug, and bleed-off rates be greatly reduced. In these cases, fractures will propagate far, but when injection ceases, consolidation occurs, and a seam of permanently emplaced solid material results. This seam may be thin, but it cannot be remobilized, thus the strains are permanent. The next injection cycle will introduce a new seam, adding to the thickness. Thus, as in the case of high bleed-off, the thickness of the waste body will increase, and eventually the same change of principal stress orientation will occur.

3 FIELD MONITORING APPROACH

The displacement field generated at the earth's surface because of waste injection must be sampled at a sufficient density to allow mathematical analysis. It is possible to measure the displacements themselves, (Δx, Δy, Δz), or the changes in the gradients of elevation at the surface, usually called the tilt vector (inclination), and comprising both a tilt magnitude and direction. Tilt is analogous to a dip and dip direction at a point on the surface. Because lateral movements Δx, Δy are usually much smaller than Δz, they are seldom collected, although in principle they could be collected to millimetre accuracy using ranging techniques based on laser interferometry. Generally, either the displacement field $\{\Delta z\}$ or the tilt field $\{\Delta\theta\}$ is collected, sometimes a combination of the two.

Advantages of displacement measurements include low cost of survey monuments, a direct physical measurement with no permanent electronic installation, and readily available geodetic quality surveying services. However, measurements cannot be carried out remotely and each data point requires a separate monument which must be physically visited to perform the measurements. Precisions of +/-0.5 mm over baselines of 75 metres can be achieved, and special monument design can eliminate near-surface effects connected to moisture or temperature changes in the ground. Alternatives to the monument approach include precision aerial surveys using conventional photography, airborne laser interferometry-based distance measurements, and SLAR satellite imagery based on interferometry. The first two are direct measurements, the second requires two surveys and a convolution of the images.

To cover large areas with levelling surveys or tilt measurements may require coverage exceeding 200 points, and a combination of technologies, such as surveys plus aerial photography, can be employed. A levelling survey takes from one to four days, therefore short-term events cannot be detected.

Tilt ($\Delta\theta$) is measured electronically, and because $\Delta\theta$ is a vectorial quantity (Δz is a scalar), it contains more information about the shape of the local displacement field. Sites are much more expensive, but remote and rapid measurements are possible, permitting "real-time" monitoring of dynamic processes with characteristic times on the order of seconds. Precisions of 10^{-7} radians are easily achieved in routine operations, greater precisions are possible (10^{-8}) at some expense. A combination of $\Delta\theta$ and Δz surface measurements carries some advantages, allowing both short-term response monitoring, and better constraints on the shape of the displacement field in the long-term. Figure 2 shows some of the principles which must be addressed in array lay-out: optimal placement of instruments in field cases is based on forward modelling and trial inversions, considering the accuracy of the reconstructions needed for the regulatory aspects of waste injection.

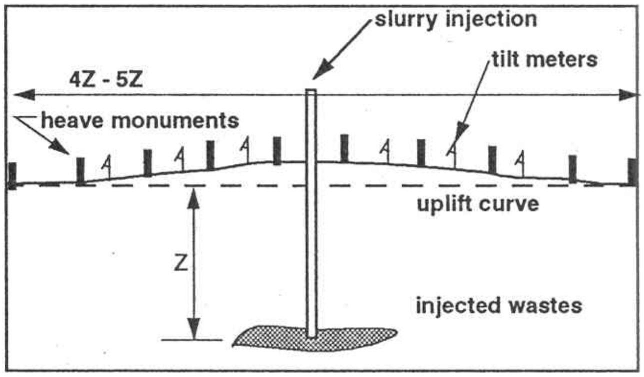

Figure 2: Monitoring Considerations

4 ANALYSIS APPROACH

Monitoring requires a means of analyzing information collected; combinations of inversion techniques and forward optimization methods are employed (Dusseault *et al.*, 1993; Bruno and Bilak, 1994). The forward optimization uses a DD (displacement discon-tinuity) approach to predict surface displacement field values, and a least-squares functional (L2 norm) is iteratively minimized to converge on the most probable solution. Each DD element is characterized by 10 independent parameters, the coordinates of a point on the DD plane (x,y,z); the dip and dip direction of the plane (Φ, Ψ), the width and length of the DD plane (W,L), two in-plane slips and expansion / contraction normal to the DD plane direction ($\delta\zeta$, $\delta\varsigma$, $\delta\xi$). Thus, if a single rectangular DD element is used for a single-well waste injection case, to give adequate areal coverage and constraints on the inversion, at least 25-30 properly distributed survey points, or 8-10 tiltmetres are necessary. As the number of planes increases, or if a statistically more probable solution is needed, the number of surface measurement points must increase. Because the injection point is known, the (x,y,z) components are constrained, and it is possible to add additional constraints based on geological knowledge and experience. For example, it is highly unlikely that, if a fracture is observed to be quasi-horizontal, its aspect ratio (W:L) could be greater than 3, or its thickness aspect ratio (D:t) less than perhaps 5. These limits can be introduced as penalty functions in the optimization process, and dynamically altered as the analysis proceeds. Figures 3 and 4 contain the results of a forward simulation using a square DD element and a circular DD approximation (many small elements). These demonstrate that for the unrealistically shallow depth of 100 m and the large (for that depth) injection volume of 50,000 m^3, only a small difference between the cases can be detected. This small difference becomes undetectable at depths greater than 200 m or for smaller volumes of injected waste, when the surface displacements for the rectangular and circular DD cases essentially concise. It can also be shown that attempts to distribute displacements such as slip or dilation in different magnitudes across the DD plane have minuscule effect on the surface displacements if the depth of the DD plane is more than 5 to 10 times its diameter. Thus, we are fully justified from an engineering perspective in using the rectangular DD with uniform values of $(\delta\zeta, \delta\varsigma, \delta\xi)$, because the random error of measurements exceeds the size of these effects in all reasonable cases.

Recent work (Wang *et al.*, 1994) shows that if pressure boundary conditions are applied to a smooth boundary elliptical crack at depth, either vertical or horizontal, the sensitivity of surface deformations is extremely slight with respect to the ellipticity of the crack. Thus, ellipticity is a second-order parameter, and we will show below that orientation and volume are first-order parametersIf nothing is known of the overburden properties, strata may be assumed to be elastically isotropic and homogeneous; if sonic log data are available, a layered stiffness model can be developed to give better results, or numerical influence functions can be developed in such a manner as to reflect the stiffness anisotropy of the overburden, more closely emulating the actual response. In fact, the effect of the value of the elastic modulus of the receiving strata and the overburden is slight (Wang *et al.*, 1994), although the relative stiffness can be more important. The overburden is assumed to respond in an elastic manner because the actual strains and stress changes are small, this has been shown to be a robust approximation (Gambolati *et al.*, 1984)..

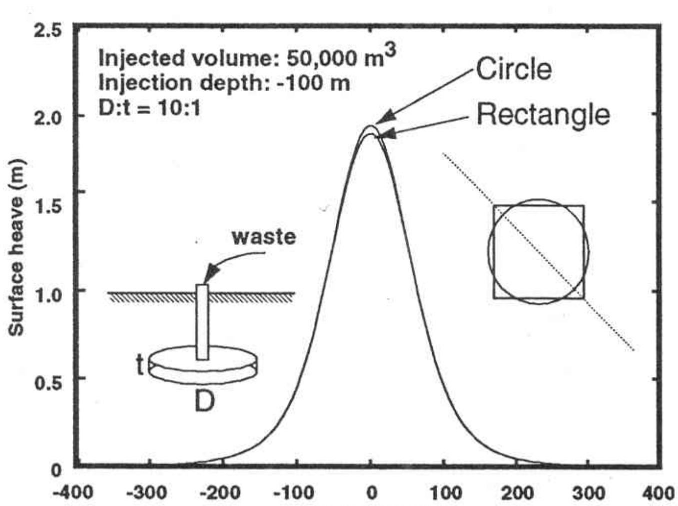

Figure 3: Surface Uplift, Shallow DD Element (A)

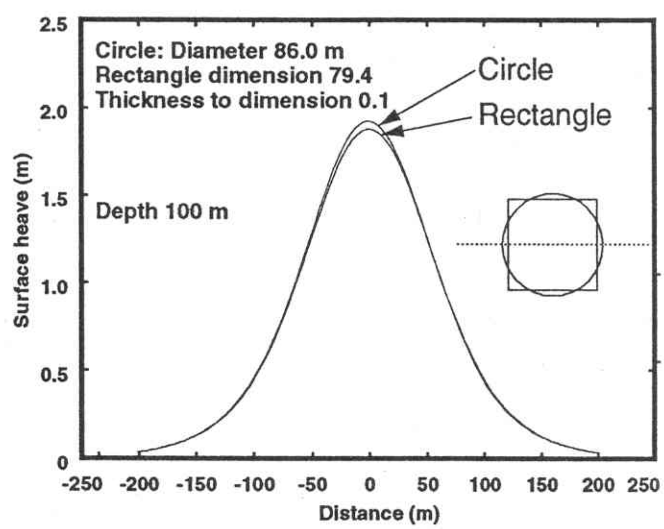

Figure 4: Surface Uplift, Shallow DD Element (B)

Analysis cannot be carried out unintelligently, particularly in complex cases with a number of DD source elements, therefore means of examining results during analysis and changing the values of weighting coefficients and penalty functions have been developed. It is far more satisfactory to monitor frequently, rather than at lengthy intervals, because the growth of the injected body and the temporal evolution of the displacement shape can be reconstructed in a more satisfactory manner, no matter what mathematical approach is used.

The goal of this article is to familiarize the reader with the measurability and mappability of injected waste bodies, based on the deformed surface shapes. The DD forward model will be used to generate a series of diagrams outlining the magnitude and geometry of the surface displacement field for a range of scenarios likely to be encountered. We will examine the sensitivity of the deformed shape to several factors such as depth, shape, and volume.

5 DEFORMATION STUDIES

The magnitude of the surface deformation is a strong (first-order) function of the depth:

$$\Delta z_{max} \propto \frac{1}{Z^n}, \quad where \quad 2 < n < 3$$

Figure 5 shows a series of typical surface uplift curves above a square horizontal waste body (L:t = 10:1) of 50,000 m³ volume. The deeper the body, the smaller Δz_{max} and the more widespread the surface zone affected. For all equant horizontal bodies in isotropic or horizontally layered strata, Δz_{max} is above the midpoint, and $\Delta\theta_{max}$ is at about 0.8Z. Even for emplacement at 2 km deep, surface strains are clearly detectable and analyzable. The shape of the surface uplift curve also depends on the in-plane shape of the body at depth, but as implied earlier, this is a relatively weak function.

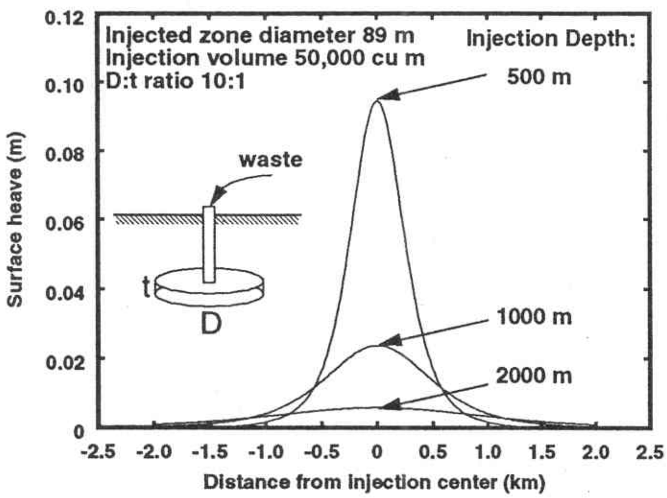

Figure 5: Surface Uplift Above a Horizontal Body

Figure 6 shows the surface vertical uplift traces across the orientation direction above the midpoint of a 3:1 (L:H) vertical waste body 1 m thick, of 50,000 m³ volume, but at different depths. Clearly, Δz_{max} is much less than for the horizontally emplaced body of equal volume at the same depth, about a factor of 6 less in general, and the central part of the surface displacement curve actually has an elevation drop.

The two points of Δz_{max} for a vertical fracture are about 0.8Z on each side of the midpoint, and the location of the point of $\Delta\theta_{max}$ is located about 0.4Z from the midpoint, generating an elongated shape parallel to the fracture azimuth. As with the horizontal fractures, the detectability is still acceptable at 2 km depth in this case because the volume change is so large. However, it is necessary to use tilts, rather than $\{\Delta z\}$ measurements. For the 500 m deep fracture, the surface displacements are sufficiently large to collect and invert $\{\Delta z\}$, although real-time monitoring is not possible in this case.

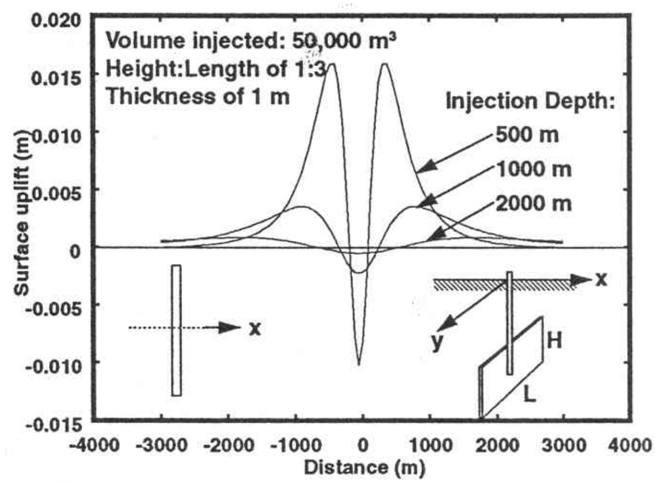

Figure 6: Surface Deformations, Vertical Body

Both the volumes injected and fracture orientation have first-order effects on the surfaced uplift shape and magnitude. For different volumes, one may estimate the surface response linearly; i.e.: for a 10,000 m³ volume at the same depth, the curve will be approximately one-fifth the magnitude of a 50,000 m³ injected volume, but the shape will be the same. From the previous two figures one may deduce that the ability to discriminate between vertically and horizontally oriented waste bodies is good, and that the azimuth of a vertical body, even at great depth, can be directly measured. To illustrate that the vertically oriented body gives a strong anisotropic directional signal, the trace of the surface uplifts along the fracture orientation are presented in Figure 7.

Note that along the center line of the surface uplift

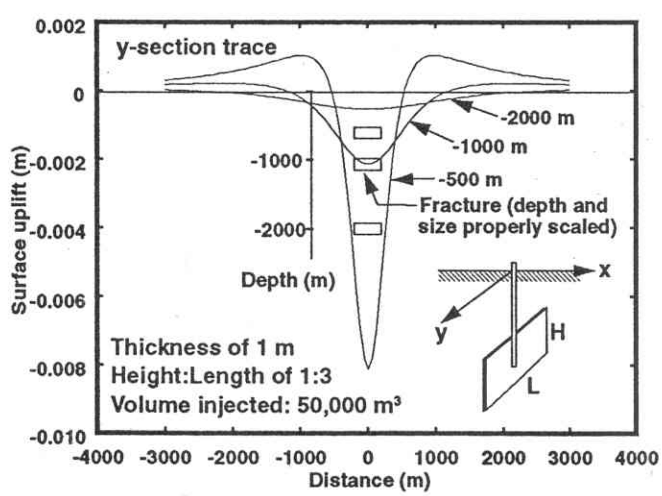

Figure 7: MidlineSurface Uplift, Vertical Body

trace for the 500 m deep vertical body, the uplift is only 8 mm. As with the other axis plot (Figure 6), there is a pronounced dip in the centre, and comparison of the two figures will demonstrate the shape anisotropy. Thus, it becomes clear how a forward optimization solution is carried out: an initial guess is made, using these forward modelling approaches and all possible constraints and information. Then, a measure of error is defined comparing the predicted values of Δz, $\Delta\theta$ at whatever {X,Y} locations the instruments were installed. Then, the estimate is iteratively upgraded until the measure of error is minimized, yet keeping faithful to the known constraints and penalties.

The maximum surface displacements encountered in horizontal waste body cases are presented in Figure 8. Each curve is the locus of magnitude of the Δz_{max} points, which occur exactly above the centre of the waste body, providing the overburden is homogeneous or orthotropically bedded with a vertical axis of symmetry. The body has been assumed to be a square DD in plan in all cases, with the same thickness ratio as Figure 5 to allow direct comparison.

The following figure shows the maximum surface

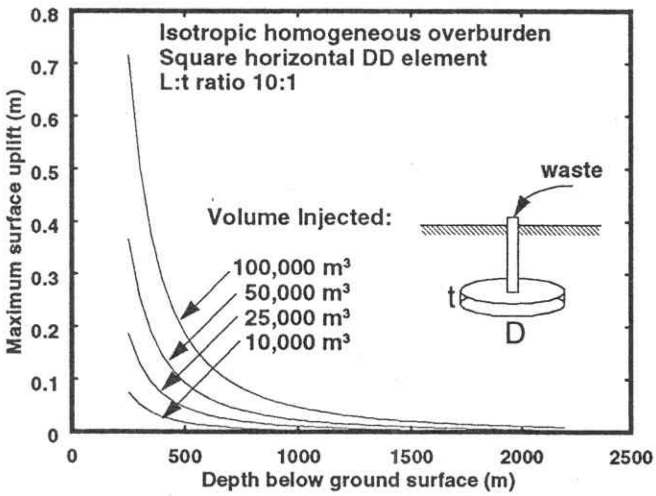

Figure 8: Surface Uplifts, Horizontal Waste Bodies

uplift for vertically emplaced waste bodies, 1 m thick, with a H:L aspect ratio of 3:1. These traces again demonstrate that the peak surface displacements for the vertical bodies are much less than for the horizontal waste bodies. The limits of reliable mapping using uplift data is perhaps Δz_{max} of 10 mm, to permit resolution enough to delimit parameters other than the azimuth, therefore in most deep or low volume cases, tiltmeters would be recommended for vertically-dominated operations. This also shows why we recommend arrays of both tilt and vertical displacement to aid in monitoring and precision inversion over a wide range of possible orientations and changes thereto.

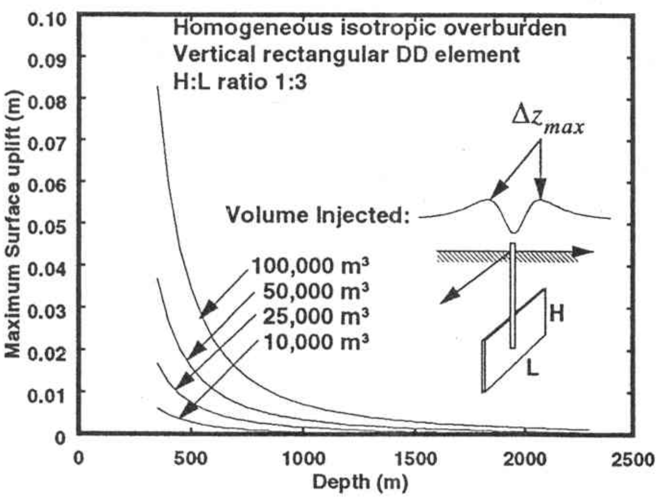

Figure 9: Maximum Surface Uplift, Vertical Bodies

Throughout this article we have repeatedly mentioned tilt values, suggesting they can be measured at a level that is much lower than Δz values. Figures 10 and 11 are representations of $\Delta\theta_{max}$ for both horizontally and vertically emplaced waste bodies, respectively.

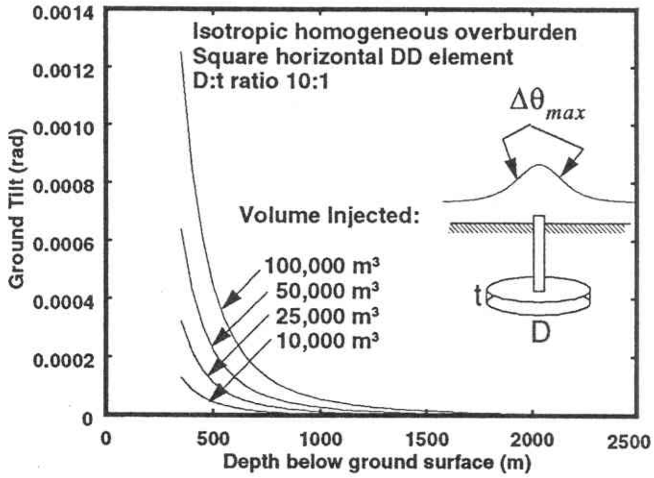

Figure 10: Maximum Tilts above Horizontal Bodies

Note that even though the absolute displacements above a vertical waste body were much lower (x6) than for a horizontal body, the maximum tilts are quite close. This is because of the very gradual change of the surface elevation over a much broader area with no changes in the curvature in the case of a horizontal body, whereas in the case of a vertical body, the sharp dip generated high tilts despite lower $\{\Delta z\}$ values.

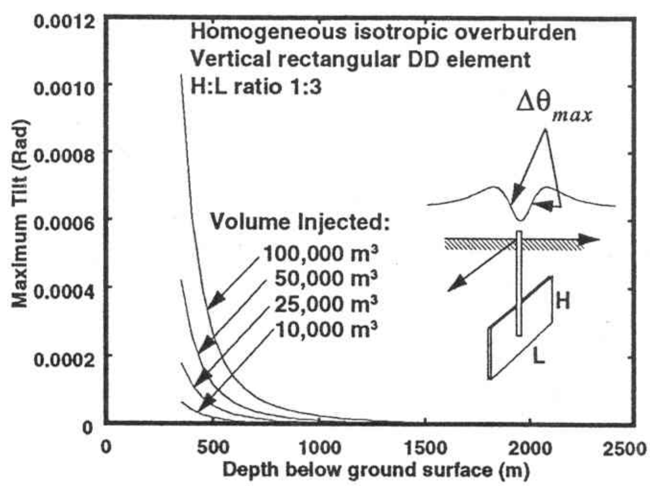

Figure 11: Maximum Tilts above Vertical Bodies

6 DISCUSSION

Based on these results, on actual field measurements on a number of operations involving injection, and on other analyses using finite elements and DD approaches (Rothenburg *et al.*, 1993), boundary integral methods (Wang, 1994), and other simulation approaches, the sensitivity of the surface displacement field to parameters describing the shape and volume of an injected body of waste can be detailed.

a. Magnitude of deformation and lateral extent of the shape at surface is highly dependent on depth.
b. Deformation magnitude is approximately directly dependent on volume of waste injected.
c. Whether the dominant orientation is horizontal or vertical in the injection zone is easy to detect as the surface deformation field changes radically.
d. Aspect ratios, both in-plane and normal to the plane, give only second-order effects at the surface, therefore the lengths of the arms of a vertical body can only be approximately resolved.
e. The lateral dimensions of the injected body, for example whether it is 25 m or 35 m in diameter, is also a second-order effect at best.

The surface displacement field, if monitored dynamically, can further constrain the shape and attitude of emplaced bodies during active injection. This is because the body size, as it increases, changes not only the magnitude of the deformed shape, but also the spread and the relative asymmetry. In dynamic monitoring, these factors can be picked up accurately by analyzing the differences in shape between subsequent sample periods (either tilt or uplift), and the time evolution becomes another dimension of the analysis procedure. In this paper, we discussed mainly detectability and the order of effects at the surface, but we will be showing an analyzed dynamic example from the field in a subsequent work.

In summary, waste injection operation monitoring can be reliably achieved through sampling and analyzing the surface deformation field repeatedly through time using a combination of surface displacement levelling or tilt measurements. The latter give more precision and provide the possibility of "real-time" monitoring, but tiltmeters are expensive electronic devices, with attendant difficulties. Surface levelling is essentially the opposite: cheap, but not conducive to continuous measurements. Thus, a combination of the two usually will be found to give the best results unless the waste injection operation is too deep, then only tilt is possible as a measure.

7 ACKNOWLEDGEMENTS

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