PS Use of Layered Formation Models in Deformation Analysis*

Eric Davis[1]

Search and Discovery Article #40853 (2011)
Posted December 12, 2011

[1]Pinnacle, San Francisco, CA (eric.davis@pinntech.com)

*Adapted from poster presentation at AAPG International Conference and Exhibition, Milan, Italy, October 23-26, 2011

Abstract

Deformation measurements are used on a regular basis to map the orientation of hydraulic fracture treatments, determine the subsurface location of steam in EOR projects, measure the magnitude and areal extent of subsidence due to production, and track injected fluids including sequestered carbon dioxide. Determining the best fit strain source to match the measured deformation requires the use of a model that predicts the deformation induced by a given strain, together with an inversion process that can manipulate the source to find the best possible match to the measured deformation. Typically, the model relies on the assumption that formation properties are homogeneous. The simplification is used primarily to save computation time, since the calculations for a layered system are far more complex. A further issue is that layer properties, particularly going all the way from the reservoir back to the surface, are often difficult to obtain within reasonable precision.

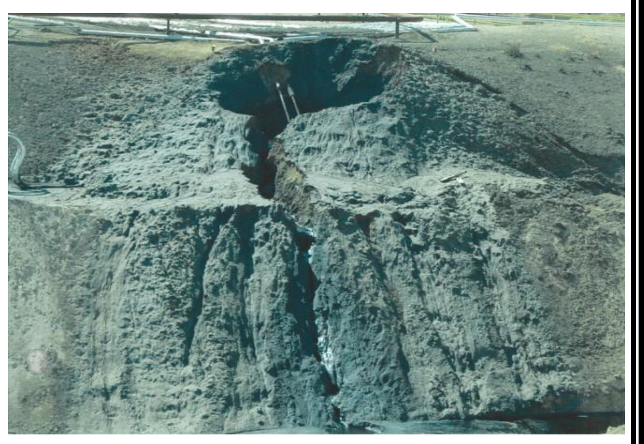
This paper explores the implications of this simplification using rigorous testing for two and three layer systems, plus select examples of more complex systems with the intent of establishing ground rules for when the introduction of a more complex layered model is justified to improve the results.

Use of Layered Formation Models in Deformation Analysis

Eric Davis
Pinnacle – A Halliburton Service
1725 Montgomery St, San Francisco, CA 94111 USA

When are the errors that result from using a homogeneous model in a layered formation too large?

Deformation measurements are used on a regular basis to map the orientation of hydraulic fracture treatments, determine the subsurface location of steam in EOR projects, measure the magnitude and areal extent of subsidence due to production, and track injected fluids including sequestered carbon dioxide. Determining the best fit strain source to match the measured deformation requires the use of a model that predicts the deformation induced by a subsurface strain source, together with an inversion process that can manipulate the source to find the best possible match to the measured deformation. Typically, the model relies on the assumption that formation properties are homogeneous. This simplification is used primarily to save computation time, since the calculations for a layered system are far more complex. A further issue is that layer properties, particularly going all the way from the reservoir back to the surface, are often difficult to obtain within reasonable precision.



The impact of laterally homogeneous formation layers is minimal with regards to the calculated orientation and areal position of a dislocations. However, the formation layers can significantly affect the surface gradient, which is the primary determinant of the source depth. The goal of this study is to determine a set of rules that can be applied to decide under what conditions the errors in calculated source depth are significant enough to justify accounting for layering effects.

1. Layered Models

The modulus variation portion of this study uses the layered model from Du (1994). The perturbation approach, simplified by allowing for constant Poisson's Ratio and moduli that vary only in the vertical direction, reduces to a surface integral for the first order solution, of the form

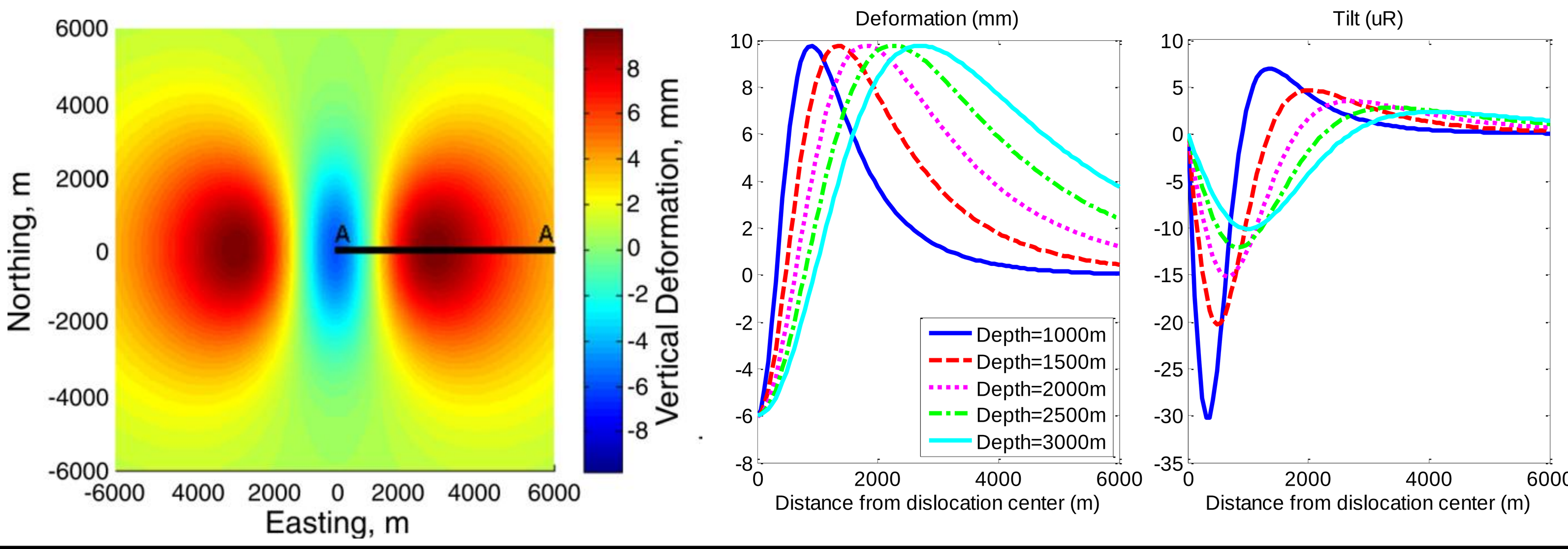
$$u_m^{(1)}(x) = -\frac{\delta\mu}{\mu_0}\int_\Gamma \sigma^{(0)}(x')G_{mi}(x,x')n_j ds(x')$$

Further simplifying the calculation, the 0th order stress $\sigma^{(0)}$ is proportional to reference modulus μ_0 while the Green's function G_{mi} is inversely proportional to μ_0, so the integrand is independent of the reference modulus, and is only a function of the system geometry and Poisson's Ratio. Using analytical solutions, Du has confirmed that the first order solution provides a result within 10% for modulus contrasts up to a factor of 10, with decreasing error for smaller contrasts. For this work, the perturbation model was coded in Matlab, and the surface integral was written using cylindrical coordinates, which behaves well close the singularity locations when a layer interface intersects the dislocation source. The cylindrical coordinate integration has the advantages that the integration parameters can self-adapt to quickly changing functions and are able to self-determine integration limits for any specified level of error tolerance, since the integrand must approach zero for large radii.

For varying Poisson's Ratio, the perturbation approach retains a volume integral. An existing code from Wang (1994,1996) provides another solution. This code uses Hankel transforms to develop a set of Green's functions that integrate the wave-number spectra functions. Although the calculations involved in this model are more complex than those for the perturbation model, the Green's functions are only a function of the layers and the observation locations, so once determined the deformation can be calculated relatively quickly. This property makes the model more suitable to inversion problems.

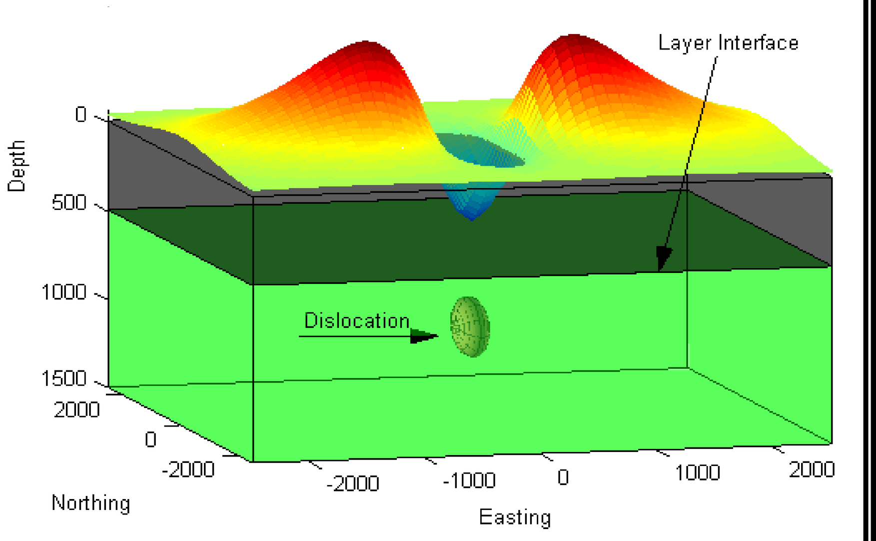
2. The Method

The distance between the peaks of the induced surface deformation serves as a proxy for the determination of source depth of a vertically oriented dislocation, using the homogeneous model (Davis 2010). By calculating the distance between the deformation peaks using the layered model, one can get a very close estimate of the best fit inverted depth that would be obtained were that deformation to be inverted on using the homogeneous model.



3. Sample System

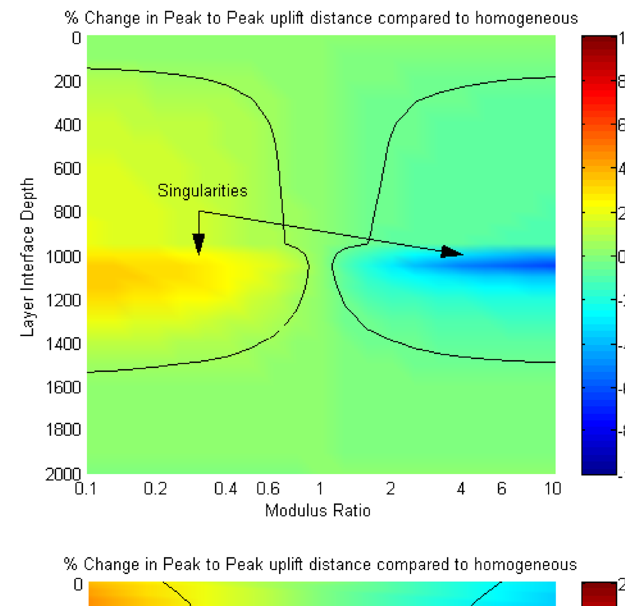
A deformation source could consist of poro-elastic swelling, or a dislocation in a horizontal, vertical, or oblique orientation. As a first step, this series of runs was conducted using a vertically oriented dislocation. The dimensions of the dislocation were kept small to minimize the impacts of singularities that arise when the layer interface coincides with the source location.

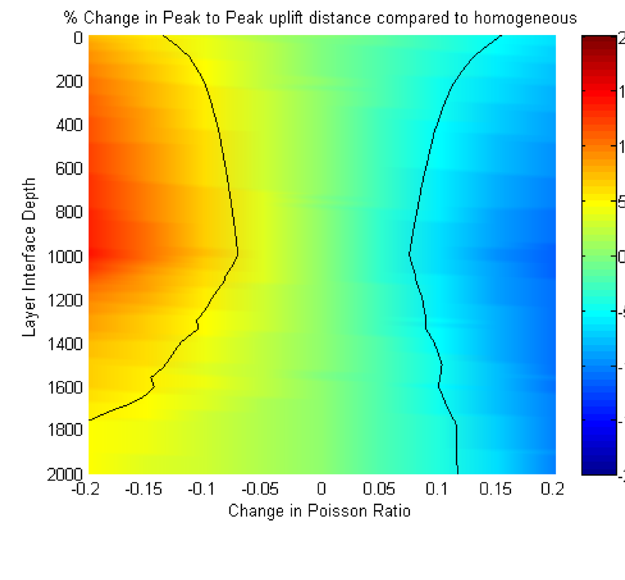


The rectangular dislocation has depth = 1000, half-length = 50, height = 20, width = 0.05. The reference Poisson's Ratio is 0.25

4. Single Interface

A single layer interface consists of a change in shear modulus or Poisson's Ratio. In the model, the depth and contrast ratios are altered across a range of values. A modulus ratio of <1 means the upper layer is higher modulus than the lower layer. The figures plot the distance between the two deformation peaks as calculated by the layered model, normalized to the homogeneous case. Uncertainty of the depth of a dislocation source is typically in the range of 10-15% of the distance between the source and the measurement location. In the figures, contour lines are drawn at +/- 5% change in the peak to peak distance as a guide to help evaluate where use of the layered model may improve the results.

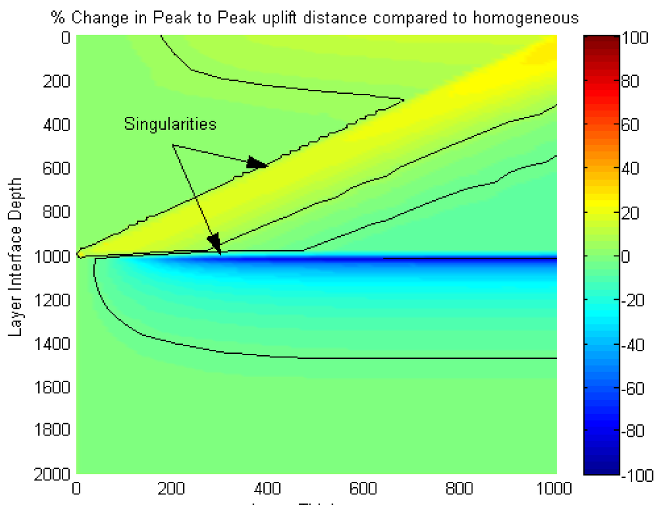




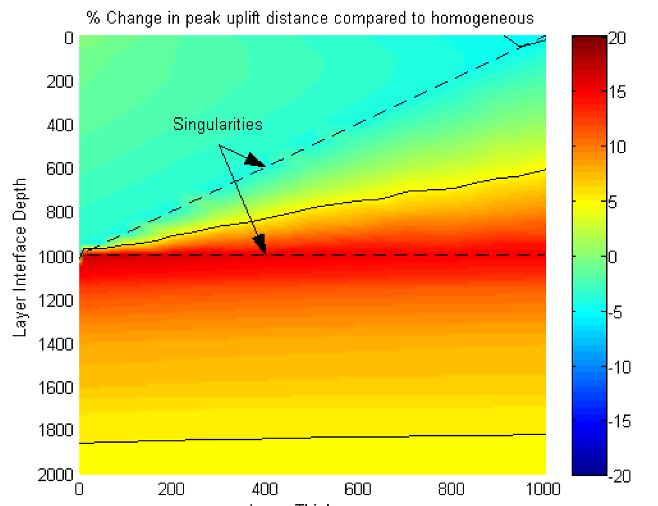
5. Dual Interface

In the dual interface model, the modulus or Poisson's Ratio above and below a pair of interfaces are identical. The value in-between the interfaces is altered by the contrast ratio. The results are plotted for two modulus contrast ratios (4 and 10) and changes in Poisson's Ratio (-0.2 and -0.15) to provide a sense for how (in)sensitive the results are to the variation in layer property values. Contour lines delineate areas where the layered model differs by 5% from the homogeneous solution.

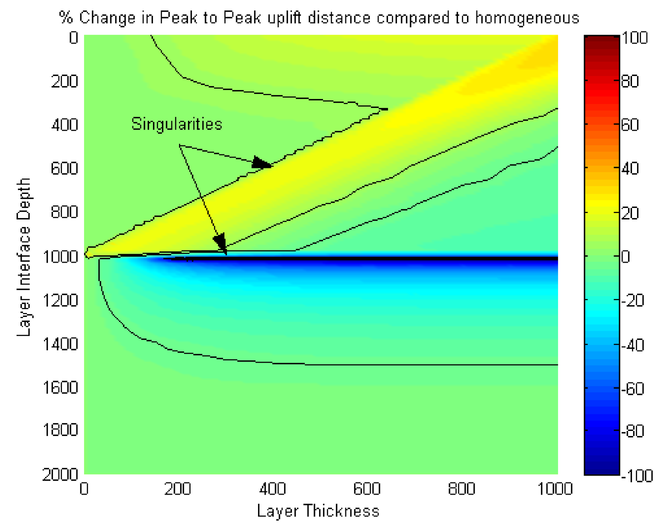
Results for changes in Poisson's ratio, particularly with small layer thicknesses below the dislocation source, bear further scrutiny.



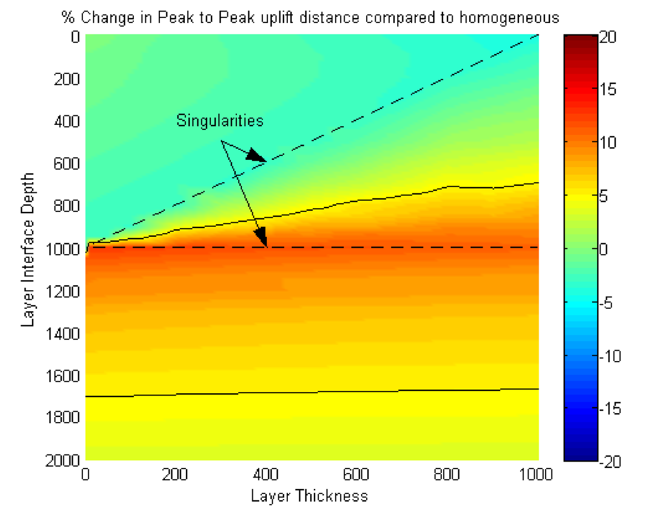
Modulus contrast ratio = 4



Poisson Ratio change from 0.25 -> 0.05



Modulus contrast ratio = 10



Poisson Ratio change from 0.25 -> 0.10

6. Conclusions

These rules are derived using only one and two interface systems, and only using a vertical dislocation, and have not yet been validated using an FE or FD comparison. They should be verified for these and other conditions, but the results suggest a compact set of rules indicating when the complication of layered models is justified.

Layer interfaces can have a measureable impact on the best fit calculated depth of a dislocation source, and should be considered for higher accuracy, under these conditions:

- The layer interface is shallower than 1.5x the source depth
- The modulus contrast exceeds a factor of 2
- The layer thickness exceeds ~20% of the source depth or is located within 1.5x the source depth.
- A change in Poisson's Ratio exceeds 0.1, or a layer with an altered Poisson's Ratio exists close to or below the source depth.

References

1. Du, Y., Segall, P., Gao, H., *Dislocations in inhomogeneous media via a moduli perturbation approach: General formulation and two-dimensional solutions*, Journal of Geophysical Research, vol. 99, No. B7, pp 13,767-13,779, July 10, 1994
2. Davis, E.J., Marsic, S., *Use of Deformation Based Reservoir Monitoring for Early Warning Leak Detection*, presented at the 10th Annual International Conference on Greenhouse Gas Technologies, Amsterdam, The Netherlands, September 19-23, 2010
3. Wang R, Martin FL, Roth F. *Computation of deformation induced by earthquakes in a multi-layered elastic crust – FORTRAN programs EDGRN/EDCMP*. Computers & Geosciences. 2003; 29: 195-207.
4. Wang R, Lorenzo-Martin F, Roth F. *PSGRN/PSCMP – a new code for calculating co- and post-seismic deformation, geoid and gravity changes based on the viscoelastic-gravitational dislocation theory*. Computers & Geosciences. 2006; 32: 527-541.