Building a 3D model of a gas field for geomechanical modelling

The main objective of geomechanical modelling is to effectively predict surface and subsurface deformation and damage due to the exploitation of subsurface natural resources and/or the subsurface storage of energy residues (e.g., hazardous waste and CO2). This objective is commonly achieved through two-dimensional (2D) stress analysis, as illustrated in the case study of a depleting gas reservoir presented in the previous issue of InFormation (May 2001). In many cases, however, the conventional 2D approach tends to oversimplify geological structures and the importance of pre-existing tectonic stresses. In this and the upcoming issue of InFormation, we will demonstrate that it is technically possible to incorporate into the geomechanical model both the full complexity of the three-dimensional (3D) geological structure of a reservoir and the possible variations in the tectonic stress field.

Workflow for integrated geomechanical modelling

We developed a workflow for integrated 3D geomechanical modelling to accurately predict deformation. The workflow integrates the tools for geological modelling, fluid flow modelling and stress analysis, allowing efficient transfer of data between the shared earth models. We used GOCAD (GOCAD, 2001) to model the 3D geometry, while relying on DIANA (DIANA, 2000) for the finite element (FE) geomechanical modelling.

The modelling process comprises three logical steps (Figure 1):

1. Mapping and modelling, in which a structural model is built.
2. Characterisation, in which property models are built by assigning volumetric identifiers.
3. Design model.

Why 3D modelling?

By adopting a 3D modelling approach, we can overcome most of the shortcomings of the conventional 2D approach, which is unquestionably suited to modelling relatively simple geological structures and pre-existing tectonic stresses. The pitfalls of the 2D approach stem from the following:

- The model cross-section has to be perpendicular to the geological structure and, at the same time, the maximal principal stress and the minimal principal stress of the tectonic stress field must both lie on the section, which is seldom the case.
- Complex stress regimes, such as a strike-slip regime, can not be modelled.
- The choice of material models is generally restricted to those models that are independent of the intermediate principal stress (e.g., the Mohr-Coulomb model).

Research framework

TNO-NITG, the geoscience institute of TNO, and TNO Building and Construction Research have entered into a close partnership for building integrated technological products for geomechanical modelling to be applied to case studies. This institutional cooperation combines the cutting-edge geomechanical expertise of TNO Building and Construction Research, which is particularly renowned for creating the world's leading geomechanical code, DIANA (2000), with the cutting-edge expertise in integrated 3D geoscience modelling approaches housed in TNO-NITG.

Why 3D modelling?

By adopting a 3D modelling approach, we can overcome most of the shortcomings of the conventional 2D approach, which is unquestionably suited to modelling relatively simple geological structures and pre-existing tectonic stresses. The pitfalls of the 2D approach stem from the following:

- The model cross-section has to be perpendicular to the geological structure and, at the same time, the maximal principal stress and the minimal principal stress of the tectonic stress field must both lie on the section, which is seldom the case.
- Complex stress regimes, such as a strike-slip regime, can not be modelled.
- The choice of material models is generally restricted to those models that are independent of the intermediate principal stress (e.g., the Mohr-Coulomb model).

Workflow for integrated geomechanical modelling

We developed a workflow for integrated 3D geomechanical modelling to accurately predict deformation. The workflow integrates the tools for geological modelling, fluid flow modelling and stress analysis, allowing efficient transfer of data between the shared earth models. We used GOCAD (GOCAD, 2001) to model the 3D geometry, while relying on DIANA (DIANA, 2000) for the finite element (FE) geomechanical modelling.

The modelling process comprises three logical steps (Figure 1):

1. Mapping and modelling, in which a structural model is built.
2. Characterisation, in which property models are built by assigning volumetric identifiers.
3. Design model.

Why 3D modelling?

By adopting a 3D modelling approach, we can overcome most of the shortcomings of the conventional 2D approach, which is unquestionably suited to modelling relatively simple geological structures and pre-existing tectonic stresses. The pitfalls of the 2D approach stem from the following:

- The model cross-section has to be perpendicular to the geological structure and, at the same time, the maximal principal stress and the minimal principal stress of the tectonic stress field must both lie on the section, which is seldom the case.
- Complex stress regimes, such as a strike-slip regime, can not be modelled.
- The choice of material models is generally restricted to those models that are independent of the intermediate principal stress (e.g., the Mohr-Coulomb model).

Workflow for integrated geomechanical modelling

We developed a workflow for integrated 3D geomechanical modelling to accurately predict deformation. The workflow integrates the tools for geological modelling, fluid flow modelling and stress analysis, allowing efficient transfer of data between the shared earth models. We used GOCAD (GOCAD, 2001) to model the 3D geometry, while relying on DIANA (DIANA, 2000) for the finite element (FE) geomechanical modelling.

The modelling process comprises three logical steps (Figure 1):

1. Mapping and modelling, in which a structural model is built.
2. Characterisation, in which property models are built by assigning volumetric identifiers.
3. Design model.

Why 3D modelling?

By adopting a 3D modelling approach, we can overcome most of the shortcomings of the conventional 2D approach, which is unquestionably suited to modelling relatively simple geological structures and pre-existing tectonic stresses. The pitfalls of the 2D approach stem from the following:

- The model cross-section has to be perpendicular to the geological structure and, at the same time, the maximal principal stress and the minimal principal stress of the tectonic stress field must both lie on the section, which is seldom the case.
- Complex stress regimes, such as a strike-slip regime, can not be modelled.
- The choice of material models is generally restricted to those models that are independent of the intermediate principal stress (e.g., the Mohr-Coulomb model).

Workflow for integrated geomechanical modelling

We developed a workflow for integrated 3D geomechanical modelling to accurately predict deformation. The workflow integrates the tools for geological modelling, fluid flow modelling and stress analysis, allowing efficient transfer of data between the shared earth models. We used GOCAD (GOCAD, 2001) to model the 3D geometry, while relying on DIANA (DIANA, 2000) for the finite element (FE) geomechanical modelling.

The modelling process comprises three logical steps (Figure 1):

1. Mapping and modelling, in which a structural model is built.
2. Characterisation, in which property models are built by assigning volumetric identifiers.
3. Design model.

Why 3D modelling?

By adopting a 3D modelling approach, we can overcome most of the shortcomings of the conventional 2D approach, which is unquestionably suited to modelling relatively simple geological structures and pre-existing tectonic stresses. The pitfalls of the 2D approach stem from the following:

- The model cross-section has to be perpendicular to the geological structure and, at the same time, the maximal principal stress and the minimal principal stress of the tectonic stress field must both lie on the section, which is seldom the case.
- Complex stress regimes, such as a strike-slip regime, can not be modelled.
- The choice of material models is generally restricted to those models that are independent of the intermediate principal stress (e.g., the Mohr-Coulomb model).
3. Engineering analysis, which gives us predictions of surface and subsurface deformation, the assessment of which is the main objective of the geomechanical modelling.

**Method for structural modelling**

In order to create consistent 3D models of the subsurface geology that will preserve the necessary degree of geological complexity and be readily convertible into unstructured FE meshes, we developed the following procedure. The main steps of this procedure are schematically presented in Figure 2.

The inputs for the modelling are depth surfaces of differentiated geological units and fault surfaces mapped in a mapping and contouring package (Figure 2a). These surfaces are usually available as gridded surfaces and first have to be converted to triangulated surfaces (Figure 2b). The surfaces also require some additional editing, for which GOCAD provides a versatile set of tools, in order to develop a consistent 3D structural model of the site of interest (Figure 2c).

Some of the geometric operations that might have to be carried out on surfaces commonly involve filling the gaps in surfaces by interpolation, extending surfaces by extrapolation, clipping surfaces and finding surface intersections. These geometric operations may alter the regular partitioning of the surfaces due to incorporation of the intersection curves. Many additional vertices, and therefore triangles, are introduced into the surface along each intersection curve. As a result, some triangles and tetrahedrons in the FE mesh will have elongated and distorted shapes which are not acceptable for producing a good, quality mesh. This problem can be overcome by resampling all borderline segments that bound model surfaces at regular intervals (Figure 2d).

The interval length can be used to control the density of vertices along the line segments, which, in turn, determines the density of triangles in the surface patches. This, in turn, determines the density of the tetrahedron mesh. The resampled keylines provide a starting point for generating resampled triangulated surfaces, which approximate the original surfaces of the structural model. The resulting surface patches marked by quality triangles define a boundary representation model that is topologically and volumetrically consistent (Figure 2e). Such a model can be meshed successfully by a 3D tetrahedral mesher, such as the one available for pre-processing in DIANA.

**Case study**

We will test the procedure described above on a case study of a depleting gas reservoir and show that it is technically possible to incorporate the complexity of the 3D geological structure of a reservoir into a geomechanical model.
**Geological setting**

The gas field under study is situated in the north-eastern region of the Netherlands. This region is well known in the gas industry because of its large Permian Rotliegend fields, including the giant Slochteren Field on the Groningen High. In addition to these large fields, smaller occurrences can be found in younger deposits, such as in the gas field under study. The reservoir of this gas field consists of clastic sediments from the Lower Germanic Trias Group, found at a depth of around 2400 m. These clastic fluviolacustrine sediments were deposited in the intracratonic Niedersaksian Basin which spreads out into Germany (Figure 3).

The reservoir structure is formed by an anticlinal structure above the Emmen Salt dome. Figure 4 shows the geological structure in the vicinity of the reservoir. The basin evolution of the Niedersaksian Basin is marked by various phases of tectonism, during which halokinetic flow played an important role. In the Permian and Triassic periods, subsidence occurred that was regionally rather uniform. This resulted in the deposition of Permian sandstones and evaporites and, subsequently, the deposition of the Triassic sediments. In the Jurassic period, more differentiated subsidence occurred through extensional WSW-ENE trending faults soling into the Permian evaporites. The extensional faulting, which was most active during the Late Kimmeridgian (ca. 150 Ma), caused halokinesis of the Permian evaporites, resulting in WSW-ENE trending lows and highs. The structures then formed were strongly reactivated through compression that culminated in the Late Cretaceous. The compressional deformation resulted in inversion of the Late Jurassic faults and generated WSW-ENE folds truncated by the Base Tertiary unconformity (Figure 4). The Base Tertiary structure shows NW-SE to NS trending grabens in the area that are in close agreement with the largest present-day horizontal stresses oriented NW-SE.

Seismic events started to occur after 12 years of production. The magnitudes recorded ranged from 1 to 3.5 on the Richter scale. All of the epicentres are located above the crest of the field. Depths of hypocentres have been indicated at or above reservoir depth, with an uncertainty of ±500 m in the vertical direction.

**Geomechanical model**

The structural model and the boundary representation model of the gas field under study, constructed in GOCAD in accordance with the procedure described previously, are shown in Figure 5. The model preserves the main structural features of the geological setting.
The boundary representation model is meshed by a 3D tetrahedral mesher in DIANA to produce a quality FE mesh, which will be used in geomechanical FE analysis (Figure 5). Conversion of the complex structural model into an unstructured mesh suitable for FE analysis is a critical step in the workflow. The mesh has to fulfil a number of geometric criteria with respect to the shape of finite elements. Triangulation is performed using an algorithm based on the principle of Delauney triangulation, which creates a set of triangles, or tetrahedrons, for a set of scattered points (the input) such that the triangle vertices are at the given data points and the triangles are as equiangular as possible. Constrained meshing, which honours the external and internal geometric constraints, has been applied in order to preserve the complexity of the 3D geological models.

Acknowledgements
This paper is a compiled version of the paper presented at the IAMG 2001 (International Association for Mathematical Geology) conference in Cancun.

Conclusions and follow-up
Integrated geomechanical modelling demonstrates that it is technically possible to incorporate the complexity of the 3D geological structure of a reservoir, including faults, into the geomechanical model. The FE stress analysis, which will be presented in the next issue of InFormation, will investigate the interplay between the remote tectonic stress and the human-induced changes in stress due to reservoir production.

References

Information:
Bogdan Orlic
T +31 30 256 46 46
E b.orlic@nitg.tno.nl

Wouter Zijl
T +31 30 256 46 45
E w.zijl@nitg.tno.nl

Rob van Eijs
T +31 30 256 45 11
E r.vanejs@nitg.tno.nl