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Coupled CO_2 sequestration simulation using Abaqus and Eclipse

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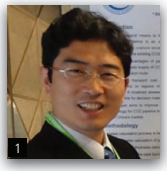

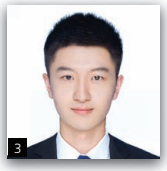
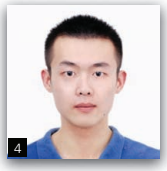
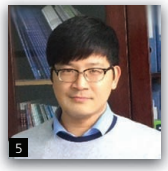

Thermo-hydro-geomechanical (THM)-coupled physical problems widely occur in geologic carbon dioxide (CO_2) sequestration (GCS), which has gained increasing attention in recent years. There are many in-house and commercial software programs developed for THM-coupled numerical simulation. However, only a few programs permit large-scale, complex analysis and prediction of GCS problems. Therefore, the authors developed an in-house code named AEEA Coupler to link two industrial standard simulation software programs, Abaqus (mechanical engineering) and Eclipse (petroleum engineering), which enable THM simulation of large-scale complex geological models (including multiple fractures and faults) possible. In this paper, the authors introduce interpolation and adaptive search algorithms and data exchange techniques between different grids using reservoir analysis and finite-element mesh methods in the mechanical analysis of a reservoir. After that, the applicability and accuracy of the AEEA Coupler are tested by comparing the results with certain benchmarks. Finally, a complicated problem is identified to demonstrate the power of the AEEA Coupler in solving coupled processes in geoscience projects.

Notation

C	constant compression coefficient
k	permeability
k_0	initial permeability
P	pore pressure
$\overline{P}$	average pore pressure
P_c	capillary pressure
P_{c0}	initial capillary pressure
P_{ref}	reference pressure
S	saturation
T	temperature
t_k , t_{k+1}	kth and $(k + 1)$th time step
u	displacement
V_p	pore volume at the pore pressure P
$V_p(P_{ref})$	pore volume at the reference pressure, P_{ref}
α	Biot's coefficient
ε	strain
Δx, Δy, Δz	grid dimensions in three directions
σ_i	stress
σ_r	residual porosity at high effective stress
σ_0	porosity when the effective stress is zero
σ_i'	effective stress
σ_M'	average effective stress
ϕ	porosity

Introduction

Thermo-hydro-mechanical (THM)-coupled physical problems occur in engineering projects such as geologic carbon dioxide (CO_2) sequestration (GCS), oil and natural gas underground sequestration, deep resource exploitation, high-level radioactive waste disposal and enhanced geothermal systems, and these problems have gained increasing attention in recent years (Fang *et al*., 2013; Li *et al*., 2009; Regenauer-Lieb *et al*., 2013; Xu *et al*., 2016). The critical research value of solving these problems, such as ensuring the safety of the engineering design, construction and operation of these projects, has gradually become more prominent. Due to laboratory research limitations, which involve the very complicated coupling of processes related to hydrogeology, geochemistry, thermodynamics

and rock mechanics, numerical simulation is usually applied in practice as an economic and effective method that permits large-scale, complex analysis and prediction. In GCS projects, the effects of physical and chemical changes and the capacity and penetration ability of reservoirs, as well as rock mechanic changes in the sequestration formation and cap rock, could be obtained by laboratory experiments and numerical simulation (Sarhosis *et al*., 2018).

THM-coupled problems in reservoir engineering are usually simulated by the following coupled methods (Minkoff *et al*., 2003; Samier *et al*., 2003).

- Constant compression coefficient. The pore volume, which is related only to the pore pressure, is adjusted in the software during numerical simulation using the following equations

1. $$V_p(P) = V_p(P_{ref})\left(1 + X + \frac{X^2}{2}\right)$$

2. $$X = C(P - P_{ref})$$

  where V_p is the pore volume at the pore pressure P; $V_p(P_{ref})$ is the pore volume at the reference pressure, P_{ref}; and C is the constant compression coefficient.
- One-way coupling. The pore pressure field and the temperature field calculated by fluid equations are applied as external loads to the mechanical model, and the results of the mechanical calculation need not be fed back to the fluid calculation. This method converges rapidly and is suitable when focusing only on the mechanics process. In the analysis of the relative displacement of a fault and the stress along the fault, one-way coupling is the most suitable method if the model sizes are the same. The existing simulators developed based on this coupling method are Eclipse 300-Visage, nonisothermal, unsaturated flow and transport-livermore distinct element code (NUFT-LEDC) and finite element heat and mass transfer code (FEHM)-Abaqus.
- Two-way coupling. The two-way coupling method (Samier *et al*., 2003) is able to couple the best software programs in fluids and mechanics areas. The fluids software and the mechanics software are run consecutively. Specifically, at a certain time step, the pore pressure and temperature are solved by the fluids software, while the mechanics software is suspended. Then, the fluids software is paused, and the calculated pore pressure and temperature are imported into the mechanics software to update certain parameters (e.g. the porosity) that are required by the fluids software at the next time step.
  The improved method also considers the relationship between porosity, permeability and water saturation, which reflects the weakening effect due to the pore fluid.
  The advantage of the latter approach is that the method is flexible and convenient. If the compression coefficients of the different regions of a reservoir are inconsistent, multiple correlation equations can then be defined accordingly. Furthermore, this two-way coupling method can be used for calculations using complex constitutive equations and geometric models. Tough2-FLAC3D, Abaqus-Eclipse and Athos-Visage are widely used software programs for this kind of coupling.
- Full coupling. In the full coupling method, explicit solutions of all partial differential equations are derived simultaneously. This method uses the same mesh in both the reservoir models and mechanical models, and the finite-volume method is usually used in reservoir simulation software, as well as mechanical simulation software. However, the full coupling method is still in the development stage and can be applied only in the reservoir and cap-rock areas without consideration of the impact of the surrounding rock boundary conditions. In addition, the computational complexity and poor convergence of the calculations result in this method being suitable only for relatively simple constitutive equations and geometric models. Popular numerical simulators developed based on the full coupling method are CodeBright, OpenGeoSys, FEHM, Dynaflow and COMSOL (Li *et al*., 2009).

However, no commercial software programs and open-source codes are available for the functionalities of solving THM coupling and tackling complex geometry. In the latest papers, THM is coupled in COMSOL (e.g. Shi *et al*., 2019) and the in-house code (e.g. Salimzadeh and Nick, 2019; Vilarrasa *et al*., 2014) can deal only with simplified geometry. In this paper, a program named AEEA Coupler is developed by linking two industrial simulation software programs – namely, Abaqus (mechanical engineering) and Eclipse (petroleum engineering), which are widely used and highly recognised in their respective fields – using the programming language Python 2.7 (Fei *et al*., 2015). After linking the two software programs, the complex non-linear mechanical response can be investigated in Abaqus – for example, the fracture reactivation and the contact behaviours between wellbores and concretes. Moreover, advanced built-in methods, such as smoothed-particles hydrodynamics and cohesive element, make better simulation possible. The AEEA Coupler is two-way coupling that enables the THM simulation of large-scale complex geological models (including multiple fractures and faults) possible and is applied to the coupled problems encountered in China's Shenhua GCS demonstration project. The Python language is an object-oriented, dynamic programming language with a very concise and clear syntax that can be used to quickly develop program scripts or develop large-scale software programs, particularly for high-level programming tasks (Fei *et al*., 2014). Accessing the Abaqus result database with Python scripts is one of the most frequently used features with obvious advantages. The Python language is used since it supports the secondary development of Abaqus with the capability to call individual modules directly in Abaqus, which can greatly improve the efficiency of software operation. The AEEA Coupler is specific to the aforementioned tools, Eclipse and Abaqus, but can be easily expanded to other tools.

In this paper, after the development of the AEEA Coupler, the applicability and accuracy are tested by comparing the results

with certain benchmarks. Then, a case of wellbore mechanics is designed to present the flexibility of the AEEA Coupler when simulating various different computational grids. Finally, some concluding remarks are provided.

Coupling mechanism of the AEEA Coupler

When two software programs, such as Abaqus and Eclipse, are linked together (i.e., coupled), the total simulation time is divided into several steps according to the calculation precision and the computer efficiency. The software programs perform calculations individually, and the parameters are transferred to each other at each time step. The effect of the effective stress on the porosity and permeability of rock, as well as the effect of the fluid pressure and temperature on rock deformation, is considered in the coupling equation.

As shown in Figure 1, a multiphase thermo-hydraulic (TH) or thermo-hydro-chemical (THC) coupling operation is first performed by Eclipse (Kuang *et al*., 2014), and then, the centre point position and the temperature, pore pressure and saturation information of the Eclipse difference grid are read by the bridging program, the AEEA Coupler. Meanwhile, the distributions of the temperature and pore pressure of the corresponding Abaqus finite-element mesh are calculated. Afterwards, Abaqus starts the THM-coupled analysis (Li *et al*., 2006), and then, the integral point position and stress information of the Abaqus finite-element mesh are read by the AEEA Coupler. Thereafter, the porosity, permeability and capillary pressure under the influence of stress are calculated and transferred to the corresponding difference grid of Eclipse by the AEEA Coupler. Regarding the role of the water retention behaviour, the default relationship is used in Abaqus. The relationships among the porosity, permeability and stress are established in the mechanics software. The relationships depend on the constitutive model selected in the mechanics software.

The entire THM analysis consists of sequential explicit coupling, and the analysis steps are shown in Figure 2. The TH(C)-coupled

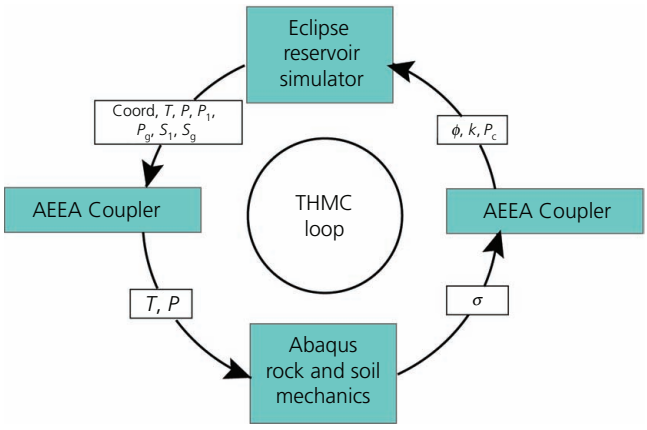

Figure 1. Schematic diagram of the AEEA Coupler. Coord, coordinates; THMC, thermo-hydro-mechanical-chemical

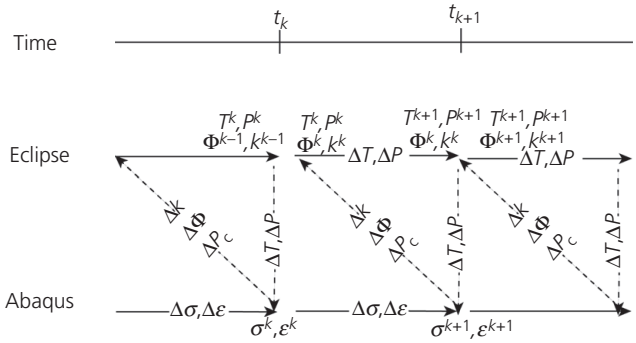

Figure 2. Coupled analysis steps over time

analysis is conducted first by Eclipse from time step t_k to t_{k+1}, and the obtained result is transmitted to Abaqus at time step t_k. Then, the THM-coupled analysis is performed by Abaqus from time step t_k to t_{k+1}, and the result is fed back to Eclipse at time step t_{k+1}, so that the next time step of the analysis and calculation can be performed by Eclipse afterwards.

In an isotropic rock mass, the porosity and permeability have a certain relationship with the average effective stress of the rock mass. A dynamic adjustment is conducted over the whole time of the numerical simulation. The relationship between the porosity, ϕ, and the average effective stress, σ'_M (Davies and Davies, 2001), is addressed as follows.

$$3.\quad \phi = (\phi_0 - \phi_r)\exp\left(5 \times 10^{-8}\sigma'_M\right) + \phi_r$$

where ϕ_0 is the porosity when the effective stress in the rock is zero and ϕ_r is the residual porosity at high effective stress, and the two parameters can be determined by laboratory experiments. The average effective stress of the rock mass can be obtained from the following equation

$$4.\quad \sigma'_M = \frac{1}{3}\left(\sigma'_1 + \sigma'_2 + \sigma'_3\right)$$

The effective stress, σ'_i, is calculated by using Equation 5 when the tensile stress is positive

$$5.\quad \sigma'_i = \left(\sigma_i + \alpha\overline{P}\right) \quad i = 1, 2, 3$$

where α is Biot's coefficient (Biot, 1941); σ_i is the stress; and $\overline{P}$ is the average pore pressure that can be calculated by using the following equation (Rutqvist *et al*., 2002)

$$6.\quad \overline{P} = S_l P_l + (1 - S_l)P_g$$

where S is the saturation; P is the pressure; and the subscripts l and g indicate liquid and gas, respectively.

The relationship between permeability and porosity is an exponential equation and is as follows (Davies and Davies, 2001)

$$k = k_0 \exp[22{\cdot}2(\phi/\phi_0 - 1)] \quad (7)$$

Meanwhile, the capillary pressure is calculated (Leverett, 1941) by

$$P_c = P_{c0}\sqrt{\frac{k_0 \times \phi}{k \times \phi_0}} \quad (8)$$

where k is the permeability; k_0 is the initial permeability; P_c is the capillary pressure; and P_{c0} is the initial capillary pressure. This equation is adopted with the aim of updating the capillary pressure by the stress (i.e. the capillary pressure is indirectly dependent on the mean stress). The same equation is also used to couple FLAC and Tough2 (Rutqvist *et al*., 2002).

Abaqus is a software program that was developed based on the finite-element method, while Eclipse is a software program that was developed based on the finite-difference method, which means that the computational grids are different between the two software programs. In Abaqus, the force is loaded on a node and the data are output at the integration point. In Eclipse, each grid has properties only at the centre point, and the coordinates of each grid are determined by the corner points. As shown in Figure 3, the data at each centre point of the grid in Eclipse are transmitted to a node in Abaqus while calculating, and then, the data obtained at an integration point in Abaqus are transferred to a centre point in Eclipse.

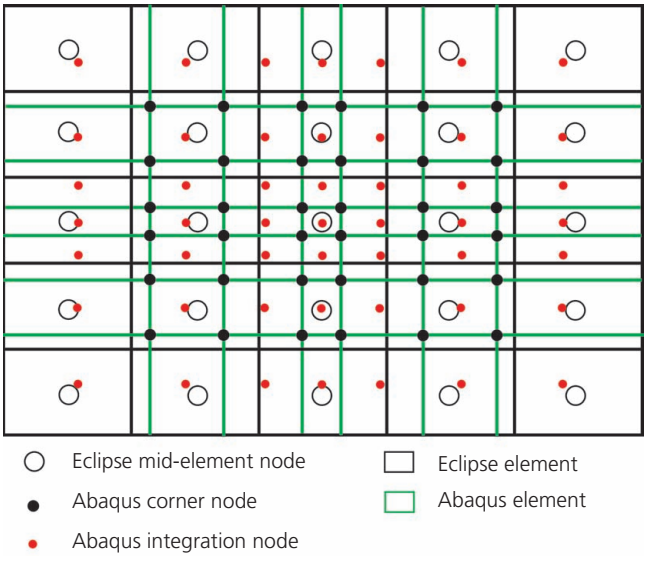

Figure 3. Grid and data transmission points between Abaqus and Eclipse

Capasso and Mantica (2006) first introduced the differential grid when dealing with finite-element mesh and finite-difference mesh and then removed certain nodes as needed and exchanged the remaining nodes into a finite-element mesh. According to this method, the data in the differential grid can be directly used. However, the number of nodes and the shape of meshes are different between the finite-element model and the finite-difference model, which suggests that this method is not applicable when the region of the finite-element mesh is only a part of the area represented by the finite-difference mesh. Dean *et al*. (2006) used the same grid to perform finite-element and finite-difference analyses, and this technique is quite simple but cannot be used as a general method.

The developed AEEA Coupler program is capable of transforming data between two different grids rapidly, accurately and flexibly even though the size, shape and mesh density are different. Thus, the numerical analysis could be more flexible, and the computational efficiency could be greatly improved.

When two different grids are used for a coupled process analysis, an adaptive search algorithm is adopted for data transmission. The assignment will be made directly if the coordinates of the nodes of the finite-element mesh and the centre points of the finite-difference mesh are coincident. Otherwise, a spherical region search will proceed, as shown in Figure 4. The initial search radius is determined by the size of the grid. If the search result does not meet the requirement, the radius size will be changed and the search will be conducted again. If the search is performed too many times, the search conditions will be appropriately eased.

Inverse distance weighted interpolation (also known as 'inverse distance weighted average' or 'Shepard method') is used when interpolating the value of the searched point to the node of another grid.

Zhang (2012) used the Shepard method for the digital elevation model, and a significance analysis of the interpolation parameters was performed. The results are addressed as follows.

- In terms of the search direction, the four-way search and the eight-direction search do not improve the interpolation precision.
- Using 8 to 12 search points is a better choice.
- When the weighted index is greater or equal to 3, the effect of the interpolation precision is not clear. A weighted index of 2 or 3 is better.
- Based on the significance analysis, the impacts of the aforementioned three factors on the interpolation precision are sorted as 'weighted index > number of search points > search direction'.

The calculation flow chart of the AEEA Coupler is shown in Figure 5.

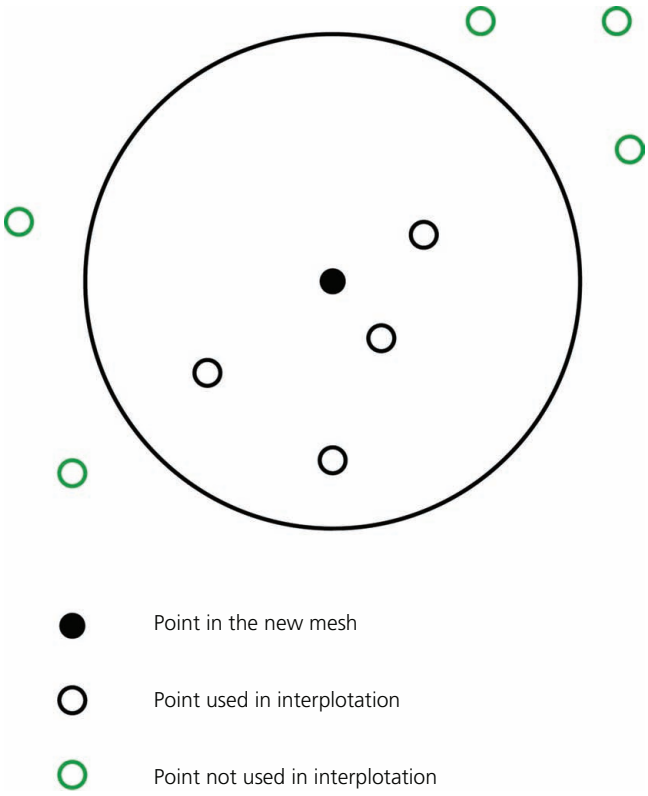

Figure 4. Diagram of the search method

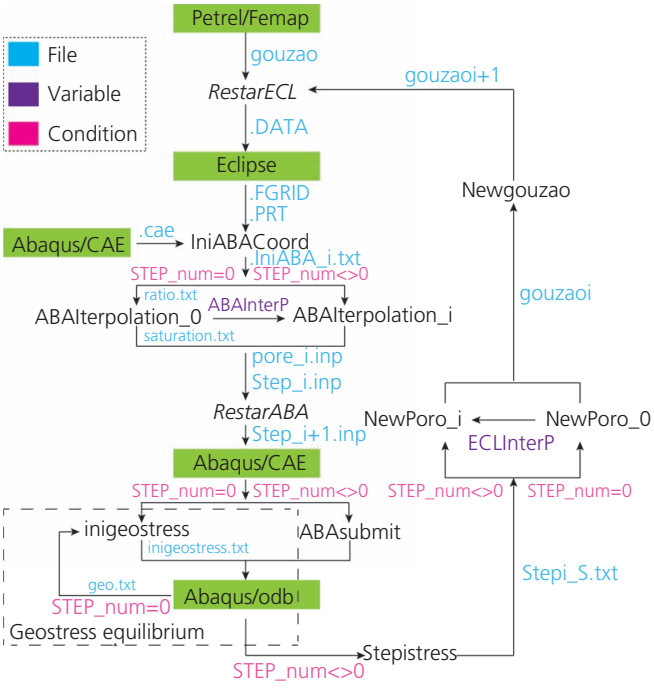

Figure 5. Calculation flow chart of the AEEA Coupler

Model validation

Benchmark SPE 79709

This section shows the accuracy of the AEEA Coupler by comparing its results with a standard example proposed by the Society of Petroleum Engineers (SPE) (Dean *et al.*, 2006). The two problems defined in SPE 79709 are simple single-phase depletion problems that illustrate the role that stress and displacement boundary conditions play in porous flow calculations. Biot's parameters α and $1/M$ are set equal to 1 and 0, respectively. Problems 1 and 2 are identical in their description except that problem 1 enforces zero-displacement boundary conditions at the vertical faces of the grid, and problem 2 applies constant horizontal stresses at the vertical faces of the grid. Figure 6 shows the stress and displacement boundary conditions for the two problems.

The grid dimensions are $11 \times 11 \times 10$ with $\Delta x = \Delta y = 60{\cdot}96$ m in the horizontal direction and $\Delta z = 6{\cdot}096$ m in the vertical direction. The top of the reservoir is at a depth of 1828·8 m. The initial in situ reservoir porosity is 0·2. The residual porosity is 0·19. The reservoir permeabilities are 50 and 5 mD in the horizontal and vertical directions, respectively. The fluid is a single-phase fluid with a formation volume factor of 1·0, a viscosity of 10^{-3} Pa s and a fluid density of 999·648 kg/m^3. The initial fluid pressure is 20·68 MPa at a depth of 1828·8 m, and the hydraulic gradient is 9794·71 Pa/m.

The elastic modulus is 68·95 MPa. Poisson's ratio is 0·3. The initial in situ solid density (the solid material without pores) is 2700 kg/m^3. The initial horizontal stress is 27·58 MPa over the entire reservoir depth, while the initial vertical stress gradient is 23 143 Pa/m throughout the reservoir. The bottom of the grid has a zero vertical displacement constraint, and all faces of the grid have zero tangential stresses. Both problems apply a normal stress

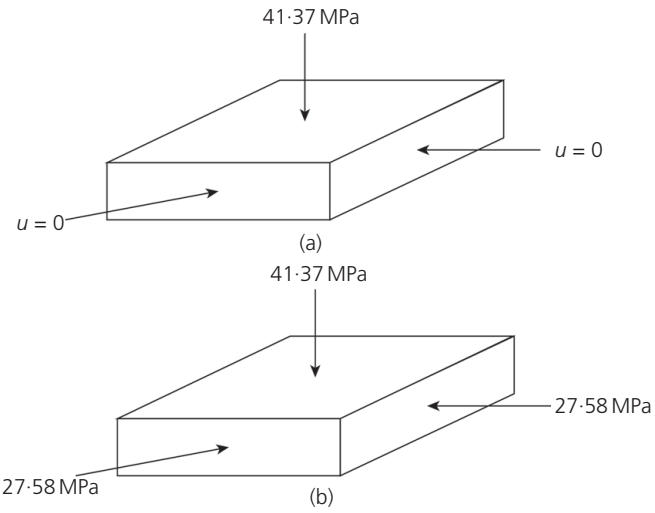

Figure 6. (a) Constrained displacement for problem 1 and (b) unconstrained displacement for problem 2 of SPE 79709 (Dean *et al.*, 2006)

of 41·37 MPa at the top of the grid, while problem 1 enforces zero normal displacements at the four vertical faces of the grid. Problem 2 applies a normal stress of 27·58 MPa at these same faces. Uniaxial strain behaviour is assumed for problem 1, and a constant total stress is assumed for problem 2.

A vertical well with a wellbore radius of 0·0762 m is completed in the centre of the reservoir and penetrates all ten layers of the grid – namely, cells (6, 6, 1–10). The well is produced at a rate of 2384·7 m^3/d for 500 d with a time step of 10 d. No-flow boundary conditions are assumed for the fluid at all faces of the grid.

Figure 7 shows how the geomechanical stress or displacement boundary conditions influence the pressure response in the reservoir, and Figure 8 shows the subsidence at the top of the reservoir at the well for problems 1 and 2. The results obtained by the AEEA Coupler were compared with the benchmark example of SPE 79709, as shown in Figures 7 and 8. Due to the different code programming principles of the two software programs and the constant fluid compressibility used in the SPE 79709, there was a slight deviation. In the case of the boundary constraints in Figure 7, the fluid compressibility decreased at the later stage when using the AEEA Coupler, which increased the production difficulty. Therefore, the average pore pressure at the later stage was slightly higher than the value obtained in the benchmark example. Figure 8 shows that the subsidence at the early stage was larger than that in the benchmark example, which is also due to the decreasing porosity and permeability obtained by the AEEA Coupler during the analysis.

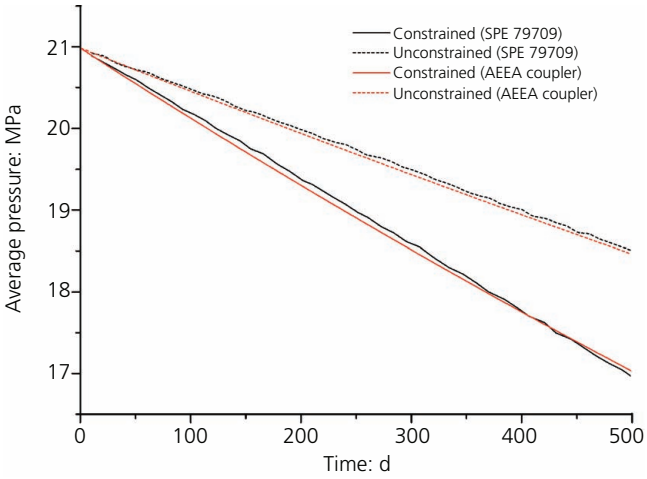

Figure 7. Average pore pressure

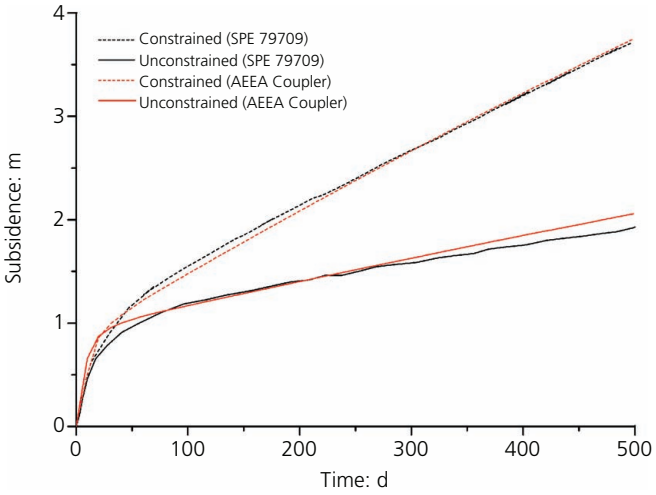

Figure 8. Subsidence at the top of the reservoir

Benchmark SPE 125760

The benchmark validation model of SPE 125760 in this section was widely used by Cuisiat *et al*. (1998), Dean *et al*. (2006), Samier and Gennaro (2007) and Inoue and da Fontoura (2009). This section shows the accuracy of the AEEA Coupler by comparison of the results with the work of Inoue and da Fontoura (2009). The model (Figure 9) contains not only the reservoir but also the surrounding rock for the accuracy of the mechanical boundaries.

The finite-difference grid and finite-element mesh were made coincident in this model. A mesh of 21 × 21 × 12 elements that was called a coarse grid and a mesh of 33 × 33 × 17 elements that was called a fine grid were used by Inoue and da Fontoura (2009). Furthermore, a comparison between the full coupling and two-way coupling method results was made as well. The results indicate that the precision was higher in the fine grid, which needs a large amount of computation. Only 7 s was needed in the coarse grid for each mechanical calculation, while the fine grid needed 47 s. Moreover, a significant difference between the results of the two-way coupling method and the full coupling method in a coarse grid was still acceptable if the precision requirement was not high.

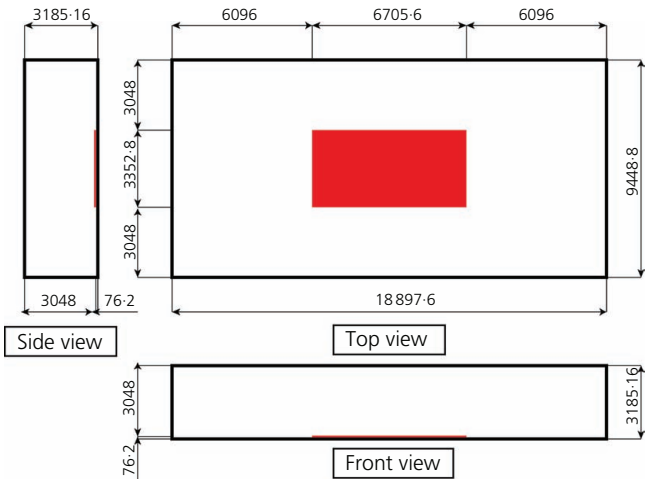

Figure 9. Geometry of the SPE 125760 problem (unit: metres)

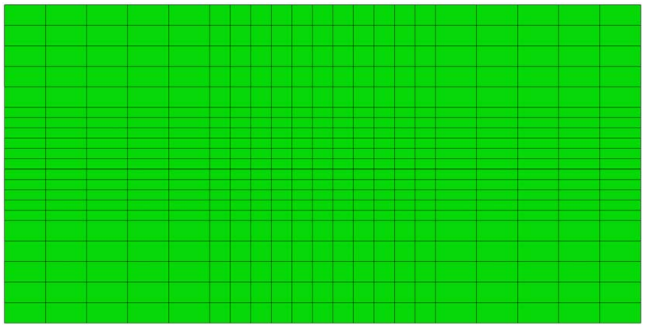

Figure 10. Coarse grid with a discretisation of 21 × 21 × 12

Table 1. Properties of the fluid and formation

Fluid flow	Value	Geomechanics	Value
Viscosity: Pa s	10^{-3}	Young's modulus of the surrounding rock: MPa	6894·8
Fluid density at 0·1013 MPa: kg/m^3	10^3		
Horizontal permeability: mD	98·6	Young's modulus of the reservoir: MPa	68·95
Vertical permeability: mD	9·86		
Porosity	0·25	Poisson's ratio	0·25
Residual porosity	0·24		

To verify the feasibility of developed AEEA Coupler in coarse grid resolutions, a grid of 21 × 21 × 12 elements was adopted in this study. The grid model is shown in Figure 10, and the material parameters used in the simulation are listed in Table 1.

The vertical stress gradient in the z-direction was 22·62 kPa/m with an initial vertical stress of 0 MPa at the surface, and the initial horizontal stresses were equal to half of the vertical stress. The boundary conditions at the side and bottom of the finite-element mesh had zero normal displacement. A vertical well with a wellbore radius of 0·0762 m and a production rate of 0·092 m^3/s was completed in all layers in the centre of the reservoir. The analysis was performed for a time period of 2000 d. The results and comparison are shown in Figures 11–13. Compared with SPE 125760, the average pore pressure decreased to 27·45 MPa after 2000 d, and the result of the AEEA Coupler was 27·39 MPa. After 2000 d, the compaction at the top of the reservoir and the surface subsidence calculated by SPE 125760 were −1·434 and −0·663 m, respectively, while the results of AEEA Coupler were −1·493 and −0·69 m, respectively. The slight deviation in the computational results was caused by the different code programming principles of the software used.

Mechanical analysis of the wellbore

In a GCS project, a safety analysis of the wellbore is of vital importance. Different software programs have different processing techniques for the simulation of a wellbore. The AEEA Coupler

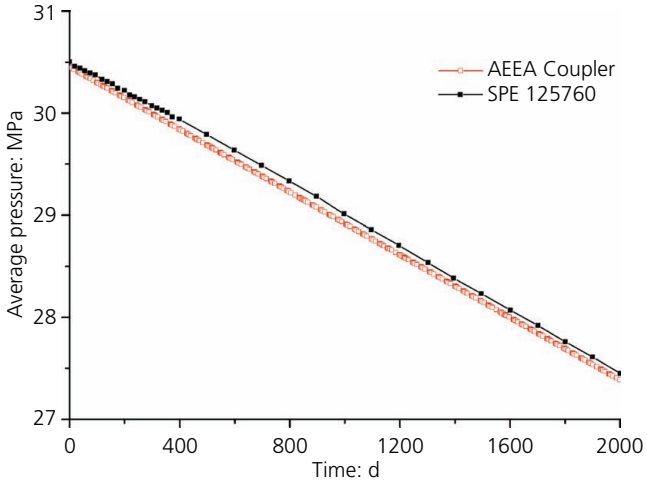

Figure 11. Average pore pressure

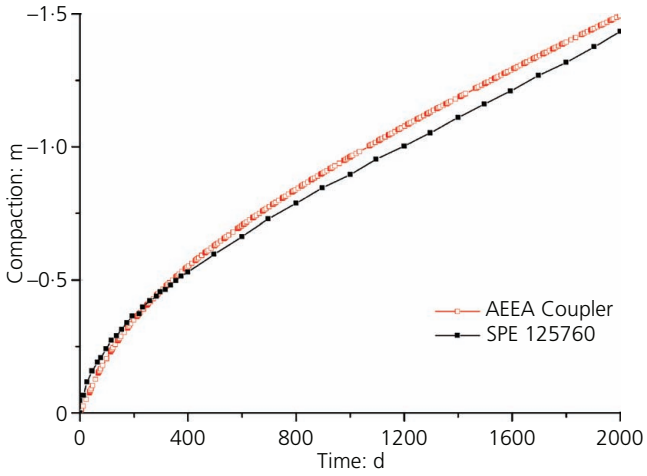

Figure 12. Compaction at the top of the reservoir

can use different grids in both Abaqus and Eclipse to analyse the wellbore performance flexibly. In particular, by using solid elements for the wellbore, different contact modes can be accomplished between the wellbore and the formation in the AEEA Coupler. This flexibility leads to a more realistic result compared with the projected wellbore path method widely used in reservoir simulations (Bostrøm and Skomedal, 2004). The model with the grid is shown in Figure 14.

The geometric model was 3000 m high, 4400 m long and 4400 m wide. A 2 m thick reservoir was buried at a depth of 1638 m. A vertical injection well, with an outer diameter of 0·09 m and a wall thickness of 0·01 m injecting carbon dioxide at a fixed pressure of 25 MPa, was completed in the centre of the reservoir. Only hydromechanical coupling was considered in the reservoir, and the solid element types of the reservoir and surrounding rock

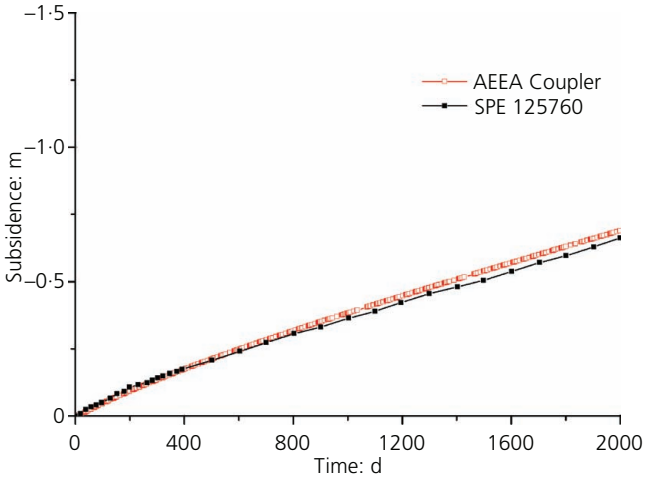

Figure 13. Surface subsidence

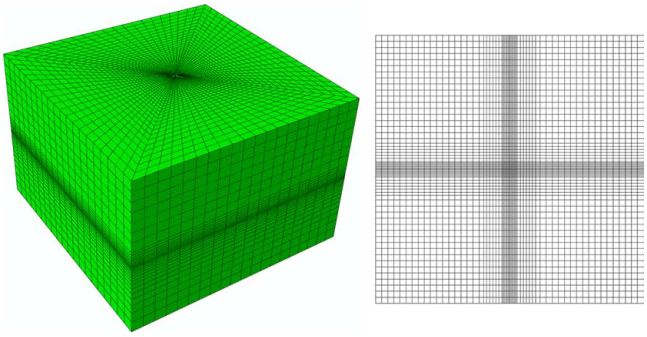

Figure 14. Computational grids

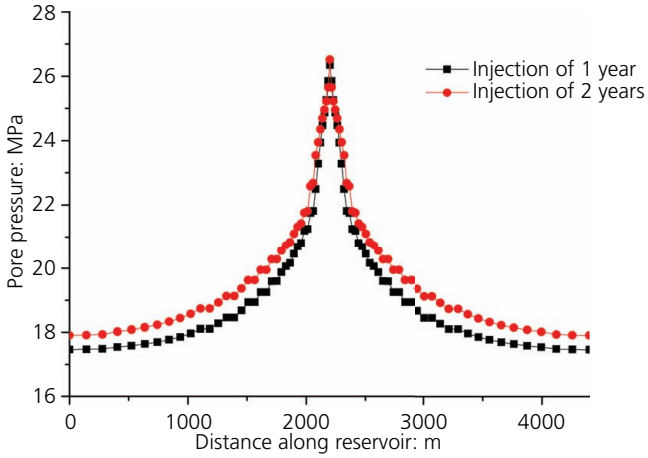

Figure 15. Pore pressure distribution at the top of the reservoir

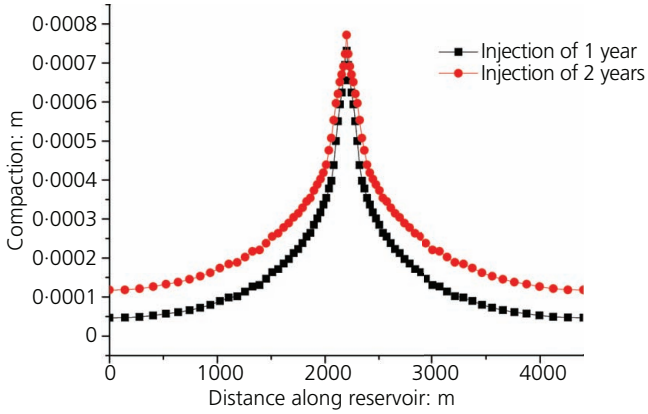

Figure 16. Displacement distribution at the top of the reservoir

were C3D8P and C3D8R, respectively. The analysis was performed for a time of 2 years. In addition, the properties of the materials are given in Table 2.

Figure 15 shows the pore pressure distribution at the top of the reservoir. After 1 year of injection, the pore pressure at the reservoir boundary increased to 17·47 MPa after 1 year and to 17·91 MPa after 2 years.

Figure 16 shows that the injection point and the reservoir boundary were uplifted by 0·731 and 0·0468 mm, respectively, after 1 year and the uplift increased to 0·772 and 0·118 mm after 2 years, respectively.

Figure 17 shows the vertical displacement of the wellbore. The injection of carbon dioxide caused the wellbore above the reservoir to rise, and the largest uplift occurred at the bottom of the cap rock, which was 0·73 mm after 1 year and 0·77 mm after 2 years.

According to the preceding performance analysis of the wellbore, as the pressure diffused around the reservoir, the displacement changed more at the boundary. For monitoring, attention should be paid to monitoring near the injection well during the first few days of injection. If there are faults in the reservoir far away from the injection well, it is necessary to pay attention to activation of the faults for long-term monitoring.

Table 2. Properties of the materials

Material	Density: kg/m^3	Young's modulus: GPa	Poisson's ratio	Permeability: mD	Porosity
Rock	2380	9	0·32	10	0·1
Steel	7850	290	0·28	—	—

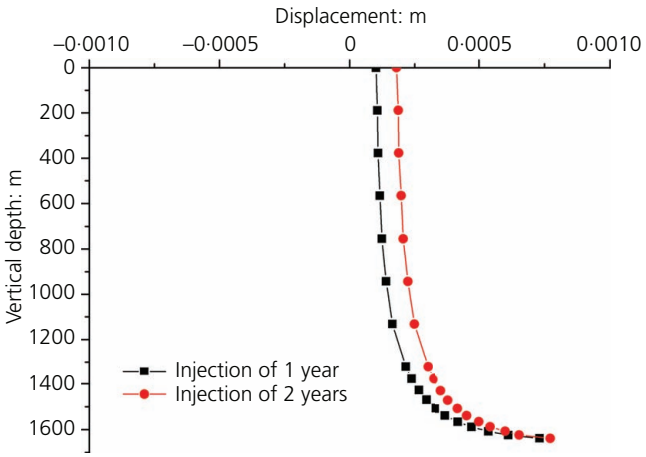

Figure 17. Vertical displacement of the wellbore

Conclusions

Numerical simulation has been an important method for studying and analysing THM-coupled problems in recent years. Based on the coupling theory of multiphysics, the AEEA Coupler was developed and verified by comparison with benchmarks to ensure its accuracy and applicability. An example of wellbore mechanics was also designed to demonstrate the flexibility of the AEEA Coupler when performing simulations between various computational grids. The applied cases in this paper are relatively simple. Complex faults and geochemical processes have not yet been considered. How to use the AEEA Coupler in a model associated with fault reactivation is still a subject that needs further research.

The main conclusions are addressed as follows.

- The AEEA Coupler not only is suitable for GCS engineering but can also be applied to the underground storage of oil and gas, exploitation of coal-bed methane and shale gas and other unconventional deep-mining projects. This bridging software can be directly called using the Python language. Furthermore, the inverse distance weighted interpolation algorithm is used to enhance greatly the speed of operation by making contributions to the calculation and data transmission between two different sets of grids in Abaqus and Eclipse.
- Verification against benchmarks SPE 79709 and SPE 125760 was conducted to illustrate the accuracy and applicability of the AEEA Coupler. The reservoir pressure and displacement distribution obtained under different boundary conditions are within acceptable limits.
- To illustrate the flexibility of data transmission between the different shapes of the finite-difference grid and finite-element mesh, the stability of a carbon dioxide injection wellbore was analysed. The pore pressure, displacement of the reservoir and vertical displacement of the wellbore were investigated during the carbon dioxide injection process, which provides some references for GCS engineering.

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