VEM application to geomechanical simulations of an Italian Adriatic offshore gas storage scenario

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VEM application to geomechanical simulations of an Italian Adriatic offshore gas storage scenario

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The storage of natural gas in underground geological formations (UGS) has been widely adopted to guarantee a real-time response to the market requests as well as to ensure National "strategic" reserves. In the recent past, the UGS and related technologies have been approached with increasing interest also in terms of CO2 sequestration and of large-scale storage of chemical energy, with the potentiality in playing a fundamental role in the energy transition process toward the de-carbonization goals.

In the context of the gas storage, both current regulations and public concerns call for geomechanical analyses to assess the safety of the infrastructures and the underground system and the recently formalized Virtual Elements Method (VEM) has been showing promising results to address such issue.

An extensive research project, involving multi-competences, dedicated to the implementation of a VEM code able to face the geomechanical aspects related to oil&gas fields is under development. The paper presents the VEM code simulation results of a realistic case study representing a typical gas field in the Italian Adriatic offshore subject to UGS. The effects of the production/injection operations, in terms of induced stress variations and consequent displacements, were calculated via the implemented VEM code and satisfactorily validated with the solution obtained from a FEM commercial software.

Keywords: *Underground Gas Storage, Virtual Elements Method (VEM), Geomechanical Analysis, Numerical Simulation.*

1. Introduction

The underground storage of natural gas is a worldwide solution adopted to guarantee a real-time response to the market gas requests, a high degree of elasticity in the management of production and transport structures, and the maintenance of "strategic" reserves (Benetatos *et al.*, 2020). It consists in seasonal and cyclical withdrawal and injection of natural gas in geologic formations. UGS dates back to the beginning of the last century and since then, hundreds of facilities have been developed worldwide. Depleted gas and oil reservoirs, deep saline formations, salt caverns and un-minable coal beds are the favorite candidates for safe geological storage of natural gas.

From the last decades, the underground storage system and related technologies have been approached with increasing interest also in terms of CO_2 sequestration and of large-scale storage of chemical energy. Strategies for CO_2 capture and permanent storage have been developed to reduce greenhouse gases in the atmosphere and contrast climate change (Bocchini *et al.*, 2017). Chemical storage implies transforming electrical power into chemical energy in the form of H_2, which can then be used as such or combined with captured CO_2 to produce green CH_4 (referred to as the gas-to-power technology).

Based on the above, it is evident that underground storage systems can play a fundamental role in the transition to a decarbonized and more sustainable energy future.

In the context of gas storage, both current regulations and public concerns call for geomechanical analyses to assess system safety conditions in terms of stored gas containment, earthquake hazard and subsidence magnitude and extension. Given the extension and complexity of the system in terms lithological, stratigraphical, and geometrical representation of the investigated volume, rock heterogeneity, as well as the involved multi-physic problems (fluid-flow, geochemical, stress-strain, between the others), 3D numerical multi-disciplinary techniques represent the best practice to simulate the phenomena under analysis.

For reservoir rock mechanics simulations, the Finite Element Method (FEM) is the reference method (Jing & Hudson, 2002), adopted by numerous commercial softwares, such as: Geomechanics (Schlumberger, 2020) and Diana FEA (DIANA FEA, 2021). Even though, the numerical methods are constantly evolving to improve the stability and accuracy of the solutions for specific application problems. Recently, the virtual element method (VEM) (Beirão da Veiga, Brezzi, *et al.*, 2013) has been formalized and adopted in different field of investigation, as it will be discussed later on in the paper. The VEM derives from the Mimetic Finite Difference method (MFD) (Lipnikov *et al*., 2014) and is considered a generalization of FEMs because it overcomes some limitations of the original method, especially related to the shape of the elements which constitutes the discretized volume or the applicability to non-conforming grids (Gain *et al*., 2014), thus allowing the presence of hanging nodes and hybrid grids.

The goal of the research presented in the paper is the validation of a Virtual Element Method code recently developed in a wider research project involving multi-disciplinary competences (Berrone, Borio, & D'Auria, 2021; Berrone, Borio, D'Auria, *et al*., 2021). The validation test was performed on a realistic case study representing a gas reservoir in the Italian Adriatic offshore. The investigation domain was selected also in accordance with the growing interest for the future conversion of this area into storage systems (for example the Adriatic Blue project by eni). Under the assumption of linear-elastic domain, the VEM results, in terms of stress variation and displacement due to fluid withdrawal/injection, were verified via a commercial FEM solver dedicated to geomechanical simulations and typically used in the oil&gas industry.

2. Considerations on the mechanical behavior of underground formations experiencing ugs

Pressure changes induced in geological formations by fluid production and/or storage affect the rock stress state and can induce surface movements.

Gas storage systems are usually generated from the conversion of exploited hydrocarbon reservoirs. During primary production, the quasi-monotonic pressure decrease occurring over decades can induce formation compaction (loading) according to a consistent time-dependent behavior of the sandy reservoir materials (Musso *et al*., 2021). When a depleted reservoir is converted into a storage, it is initially refilled with gas; this phase generates a pressure increase and thus a decrease of the effective stresses (unloading). The subsequent cycles of gas withdrawal/injection (loading/unloading) occur in the elastic field, with a stiffer behavior than in primary production. The simulation of the deformations induced by gas withdrawal/injection cycles requires an appropriate choice of the relevant parameters by selecting the reference range of strains of the process from lab tests (Marzano *et al*., 2019; Rocca *et al*., 2019). Furthermore, the transverse isotropy of the clastic formations can affect their mechanical response during storage cycles, as in the case of wellbores (Deangeli *et al*., 2021; Deangeli & Omwanghe, 2018; Parkash & Deangeli, 2019).

The UGS-related pressure variations due to the withdrawal/injection phases affect the formation cyclically and over relatively short periods (typically 5-7 months); consequently, seasonal and cyclical ground movements can be induced and detected. In details, the gas production during winter period induces an increase of the effective stresses basically in the reservoir formation and its compaction with a consequent subsidence at the ground level; instead, the summer injection activities induce a decrease of the effective stresses and the expansion of the formation with a consequent surface uplift. The behavior is commonly referred as the 'earth breathing' phenomenon.

Different researches focusing on the storage systems located in the Po Plain at around 1000-1500 meter-depth (Benetatos *et al*., 2020; Codegone *et al*., 2016; Coti *et al*., 2018) highlighted the consistency between the cyclical pressure variations affecting the reservoirs and the induced ground movements acquired by InSAR techniques. The mechanical answer of the investigated UGS systems was calibrated in terms of induced ground movements, on the basis of superficial movement survey and of the geomechanical data retrieved from well logs, *in situ* tests and lab analyses. The results indicated that the formations affected by gas injection/extraction behave nearly elastically, in agreement with previous works (Ferronato *et al*., 2013; Teatini *et al*., 2011).

3. Numerical method

The Virtual Element Method (VEM) is the latest evolution of the Mimetic Finite Difference (MFD), with various points of contact with the Virtual Element Method (FEM) so as to represent an important generalization (Beirão da Veiga, Brezzi, *et al*., 2013; Beirão da Veiga *et al*., 2014, 2016a, 2017). The key aspect of this approach consists in preserving the polynomial accuracy that is ensured on not necessarily convex polyhedral elements and in the presence of hanging nodes. Their innovative feature consists in the use of a local approximation space which includes polynomial functions that do not have explicit expression (hence the name of *virtual elements*). Indeed, explicit integration of shape functions for the stiffness matrix evaluation is avoided, thus it is only necessary to carefully choose the degree of freedom of the elements where the solution is calculated to preserve the method stability and accuracy. All this is possible by applying suitable projection operators in place of the unknown polynomial functions for the determination of the components necessary for the evaluation of the solution (Ahmad *et al.*, 2013). VEM have been already employed to a variety of engineering problems such as linear elasticity/inelasticity applications (Beirão da Veiga *et al.*, 2015; Beirão da Veiga, F, *et al.*, 2013) and fracture mechanics (Benedetto *et al.*, 2018). In the context of geomechanics, the implementation of VEM, although limited, has shown promising results. In particular 3D compression has been investigated by VEM over corner-point and polyhedral grids describing sedimentary formations (Andersen *et al.*, 2017a, 2017b). Analysis was performed on the accuracy of the solution respect to the approximation of the bilinear form and of the loading term on structural complex geometries, to the presence of cells with non-planar faces and to the coupling with fluid flow simulations.

The research project has the aim to implement a VEM code dedicated to the simulation of the stress-strain response of deep natural formation subject to fluids production and/or storage. In the present paper the validation test concerns the solution the variational formulation of the momentum balance equations with bilinear form, with u, ν defined in the Virtual Space V (eq. 1), under the assumption of small deformations and isotropic linear elastic constitutive law, depending on Young's Modulus (E) and Poisson's ratio (ν) (eq. 2). $\Omega \subseteq \mathbb{R}^3$ represents the domain of investigation with boundary Γ partitioned in disjoint non-trivial surfaces Γ^D (lateral and bottom surface) and Γ^N (top surface) and mixed homogeneous boundary conditions implicitly supposed (eq. 3). The implemented VEM are of order 1 for convex polyhedra, therefore the degrees of freedom coincide with the vertices of the element. The discrete local problem is expressed in eq. 4, $\forall \nu_h \in V_h$, where $V_h = \left\{ v_h \in V : v_{h|E} \in V_h^E \forall E \in \mathcal{T}_h \right\}$ and $\left\{ \mathcal{T}_h \right\}_h$ is a tessellation of Ω into disjoint non-overlapping polyhedral elements E. The space V_h^E is defined in eq. 5, where $H^1(E)$ is the space of functions having a square-integrable gradient on E, ∂E indicates the set of edges of the polyhedron, $P_1(E)$ is the space of polynomials of degree lower than or equal to 1 and the symbol Π_1^0 indicates a suitable projection on the polynomials of the VEM function, which can be calculated from the degrees of freedom (details in (Ahmad *et al.*, 2013; Beirão da Veiga *et al.*, 2014). As the stabilization form is $S(\cdot,\cdot)$, it is sufficient to choose the scalar product of the degrees of freedom of the two involved functions. As forcing term is imposed the variation of the pore pressure (Δp) induced by the production/injection operations (eq. 6).

For the calculation of the polynomial projection matrices, reference was made to (Beirão da Veiga *et al.*, 2014, 2016b) and for the solution of the linear system the preconditioned conjugate gradient method was then applied (Saad, 2003).

4. Case study

The case study reported in the Benetatos *et al.*, 2017 paper was adopted to validate the VEM approach. The main info about the case study are summarized in the following; further details can be found in the reference paper. Information about the geological and structural characteristics, geological and mechanical properties, production history of both onshore and offshore Italian hydrocarbon fields were collected from technical reports and public data. All the information was used to define a synthetic 3D model representative of the off-shore Adriatic panorama. A simplified regional-scale stratigraphy consisting of continuous and homogeneous geological formations representa-

$$a(u,v) := \int_\Omega \sigma(u) : \varepsilon(v) d\Omega \qquad (1)$$

$$\sigma(\varepsilon) = \frac{E}{(1+\nu)}\varepsilon + \frac{E\nu}{(1-2\nu)(1+\nu)} tr(\varepsilon)\mathbb{I} \qquad (2)$$

$$\begin{cases} u = 0 & \text{on} \quad \Gamma^D \\ \sigma \cdot n = 0 & \text{on} \quad \Gamma^N \end{cases} \qquad (3)$$

$$\begin{gathered} \int_\Omega 2\mu\varepsilon[\Pi_0^0(\nabla u_h)] : \varepsilon[\Pi_0^0(\nabla v_h)] d\Omega + \int_\Omega \lambda \Pi_0^0(\nabla \cdot u_h)\Pi_0^0(\nabla \cdot v_h) d\Omega + \\ +(2\mu+\lambda) S[(\mathbb{I} - \Pi_1^0)u_h, (\mathbb{I} - \Pi_1^0)v_h] = \int_\Omega b \Pi_1^0(v_h) d\Omega \end{gathered} \qquad (4)$$

$$V_h^E = \left\{ v \in H^1(E) : \Delta v \in \mathbb{P}_1(E), \quad v \in \mathbb{P}_1(e) \forall e \in \partial E, \quad v \in C^0(\partial E) \right\} \qquad (5)$$

$$b = -\nabla \cdot (\Delta p \mathbb{I}) = -\begin{pmatrix} \frac{\partial(\Delta p)}{\partial x} & \frac{\partial(\Delta p)}{\partial y} & \frac{\partial(\Delta p)}{\partial z} \end{pmatrix} \qquad (6)$$

tive of the Po Valley and Adriatic regions was assumed. The reproduced gas reservoir is an axially symmetric anticline trap at around 1500 meter depth, bounded by a lateral aquifer. The hosting formation consists of a sandy interval, 100 m thick, belonging to the turbiditic sand-clay alternation. The caprock is a 20 m continuous clay layer belonging to the same turbiditic sequence (Figure 1).

For the scope of the present research, we adopted the multi-physics 3D numerical simulation approach used by (Benetatos *et al.*, 2017) to reproduce the domain of investigation, to simulate the induced pressure variation and to evaluate the geomechanical behaviour of the system (Figure 1). In particular, on the basis of the same geological model, a sensitivity analysis was performed to sufficiently extend its dimensions so that the boundary effects on the calculated solution by the numerical solvers of the geomechanical problem can be considered negligible. Additionally, we prolonged the fluid flow analysis considering not only a ten year primary production period but also simulating successive gas storage injection/production activities. Figure 2.A shows the variation of the average static pressure of the system during the primary production (t_0 to t_2), the re-pressurization period due to the lateral aquifer support (t_2 to t_3), and the storage phase (t_3 to t_6). From t_1 on (t_1 corresponds to the minimum static pressure recorded during primary production) the activation of the aquifer shows its effects in term of system re-pressurization.

The spatial/temporal evolution of the pore pressure obtained via the multiphase flow simulation represents the forcing function applied to the geomechanical model. The geomechanical model was adopted to simulate the evolution of stress-strain field and of the effects in terms of induced sea floor movements via both FEM and VEM methods. The mechanical analyses of all the timesteps were developed in the elastic domain, the only constitutive law currently implemented in the VEM code. Other constitutive models (such as Mohr-Coulomb yield function) are currently under implementation, and they will widen its application domain. To reproduce the stiffer behavior of the formation during the re-pressurization phase and the storage cycles (t_2 to t_6), a Young's Modulus value 3 times the one assumed during the depletion phase (t_0 to t_1) was adopted (Codegone *et al.*, 2016; Coti *et al.*, 2018).

5. Discussion

On the basis of the elastic hypothesis, the VEM and FEM geomechanical simulations were run only

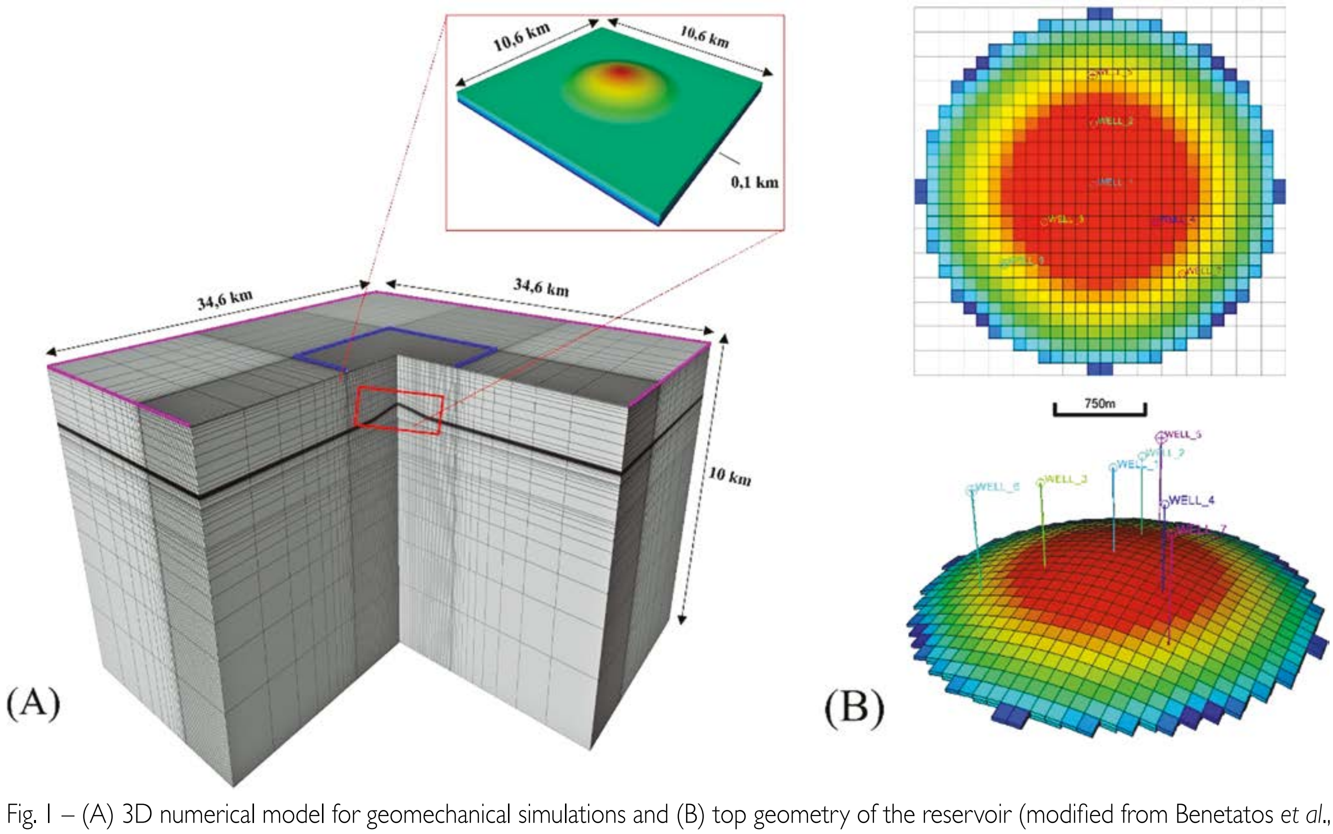

Fig. 1 – (A) 3D numerical model for geomechanical simulations and (B) top geometry of the reservoir (modified from Benetatos *et al.*, 2017).

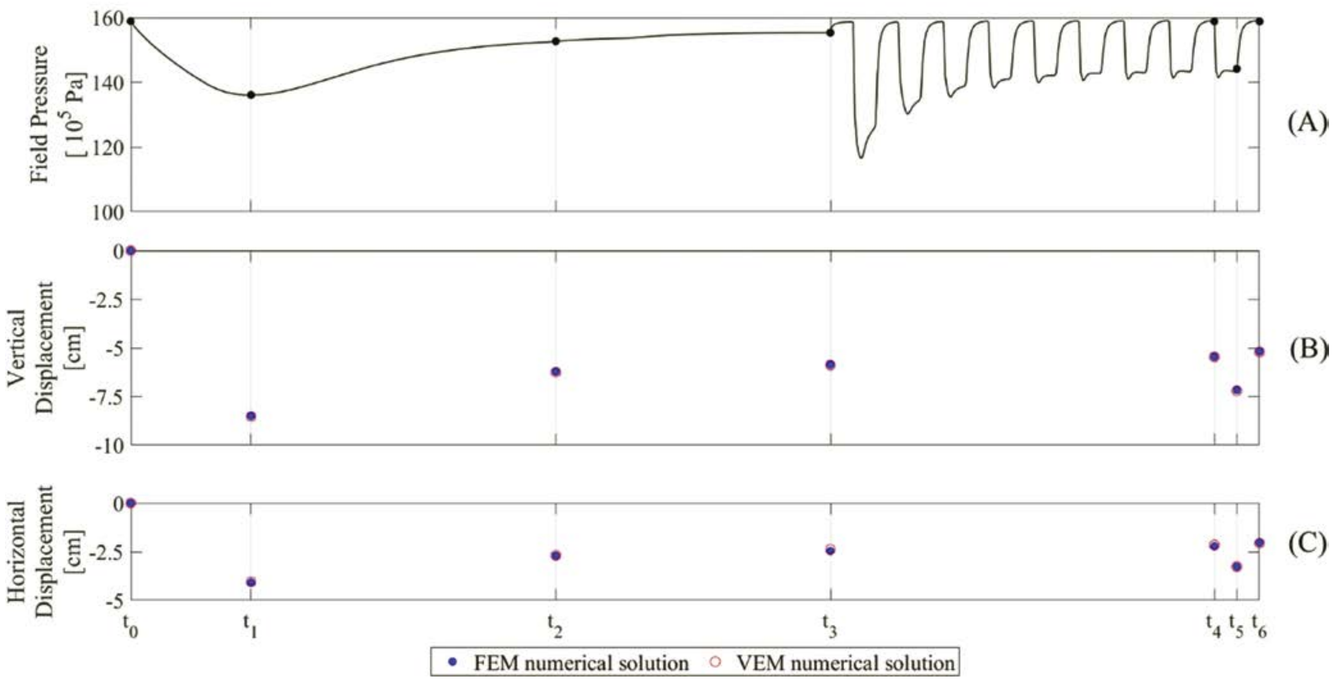

Fig. 2 – (A) The static pressure evolution in time. Black markers are the geomechanical timestep of analysis. Comparison between VEM and FEM results in terms of (B) vertical displacement at Cell#1 and (C) horizontal displacement at Cell#2.

for the timesteps highlighted in Figure 2.

Figure 2 compares the evolution of the punctual displacement at sea floor (50 m below sea level), both for the vertical (Figure 2B) and horizontal (Figure 2C) components, and for each time step of analysis. Two reference cells, Cell#1 and Cell#2, were assumed (Figure 3A): they correspond to the positions of the maximum vertical and horizontal displacement, respectively. Due to the radial symmetry of the system, only one cell is sufficient to describe the horizontal components of the displacement.

VEM results were also shown in terms of displacement and stress distribution maps. Comparison of the two solver solutions, instead, are reported as trends along two reference segments, the HH' horizontal segment on the top surface and the VV' vertical segment, zooming on the reservoir (-1200 m to -2000 m) (Figure 3B). This choice is constrained to the data availability: indeed, FEM commercial software exposes the centroid average value, instead of the nodal one. Two representative timesteps of the storage phase were identified for the comparison: t_5, i.e. the end of a production cycle, and t_6, i.e. the end of an injection cycle.

Figure 4 refers to the end of the production cycle, t_5: (A) and (C) show the maps of the vertical and horizontal displacements at the sea floor computed by VEM code. In (B) and (D) the comparison between the VEM and FEM results along the HH' horizontal segment is plotted.

Figure 5 refers to the effective stress variation induced by a production cycle (from t_4 to t_5): (A) and (C) show the distribution of the horizontal and vertical effective stress variation computed by VEM code along a vertical section throughout the reservoir. In (B) and (D) the comparison between the calculated VEM and FEM effective stress variation along the VV' vertical segment is displayed.

Figure 6 and Figure 7 are specular to Figure 4 and Figure 5 as they refer to the injection cycle form t_5 to t_6.

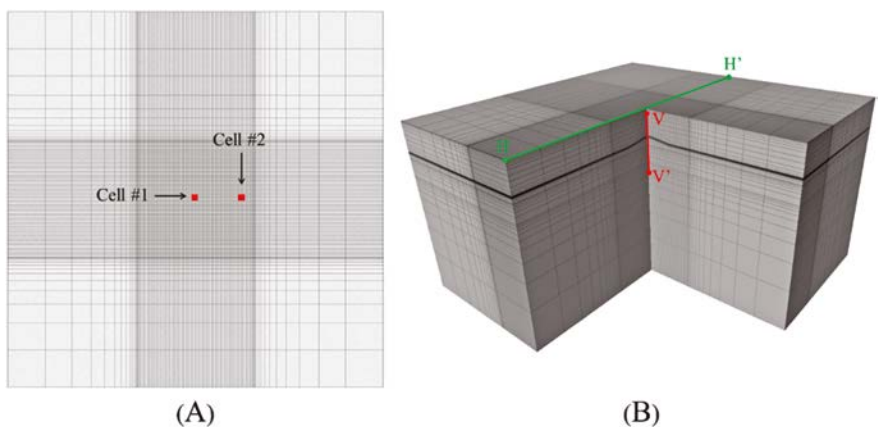

Fig. 3 – (A) the positioning of Cell#1 and Cell#2 at the grid top and (B) vertical VV' and horizontal HH' segments adopted for the comparison between VEM and FEM results.

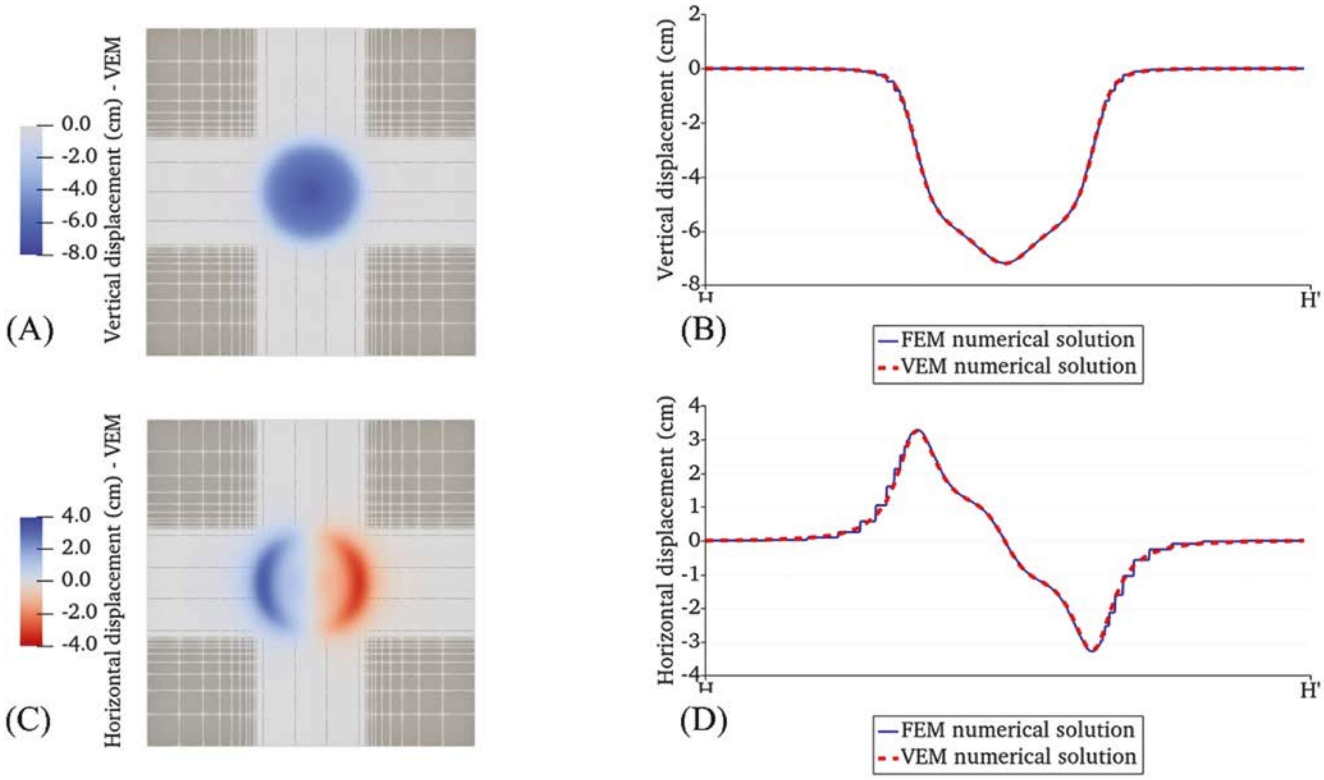

Fig. 4 – **End of production cycle – timestep t5 –** Vertical displacement: (A) map of the VEM results at the sea floor and (B) comparison between the VEM and FEM results along HH'. Horizontal displacement: (C) map of the VEM results at the sea floor and (D) comparison between the VEM and FEM results along HH'.

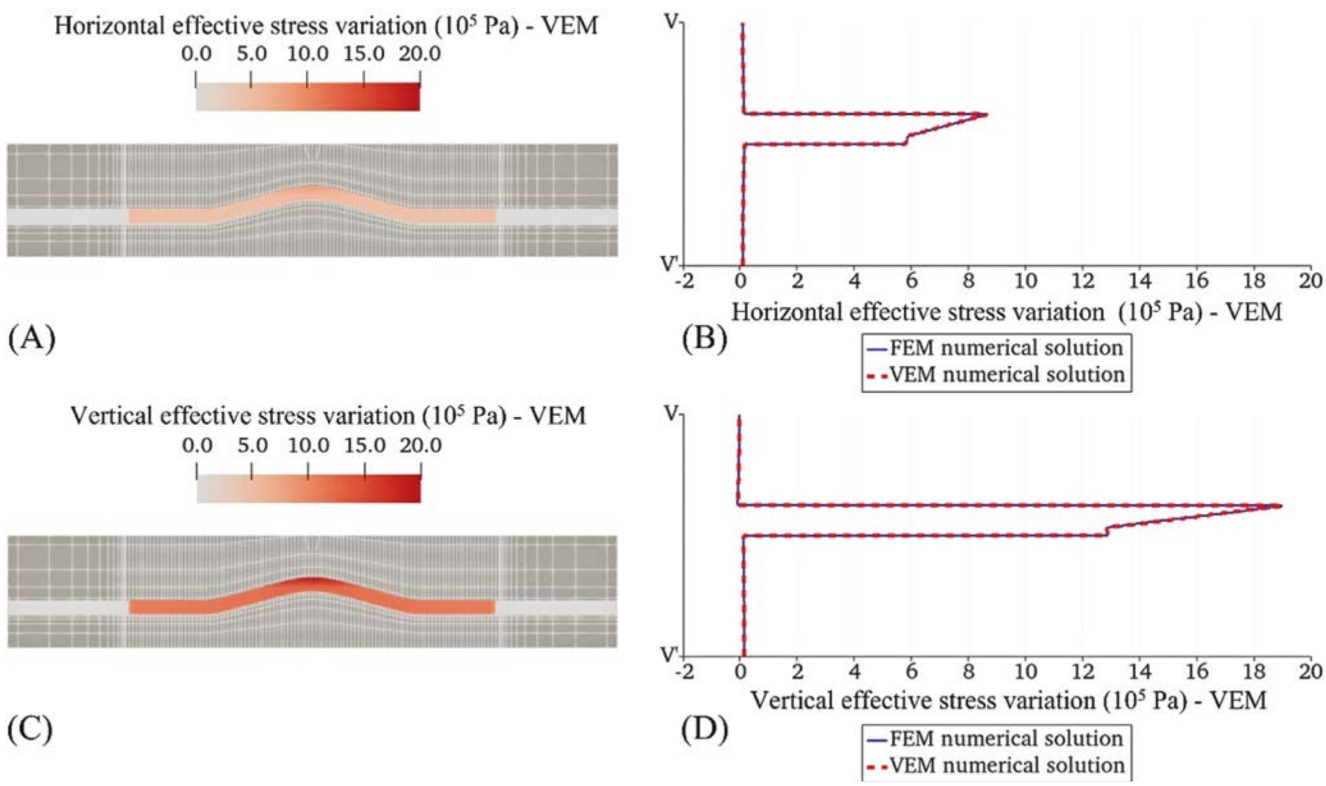

Fig. 5 – **End of production cycle – timestep t5 –** Variation of the horizontal effective stress: (A) distribution of the VEM results along a vertical section throughout the reservoir and (B) comparison between the VEM and FEM results along VV'. Variation of the vertical effective stress: (C) distribution of the VEM results along a vertical section throughout the reservoir and (B) comparison between the VEM and FEM results along VV'.

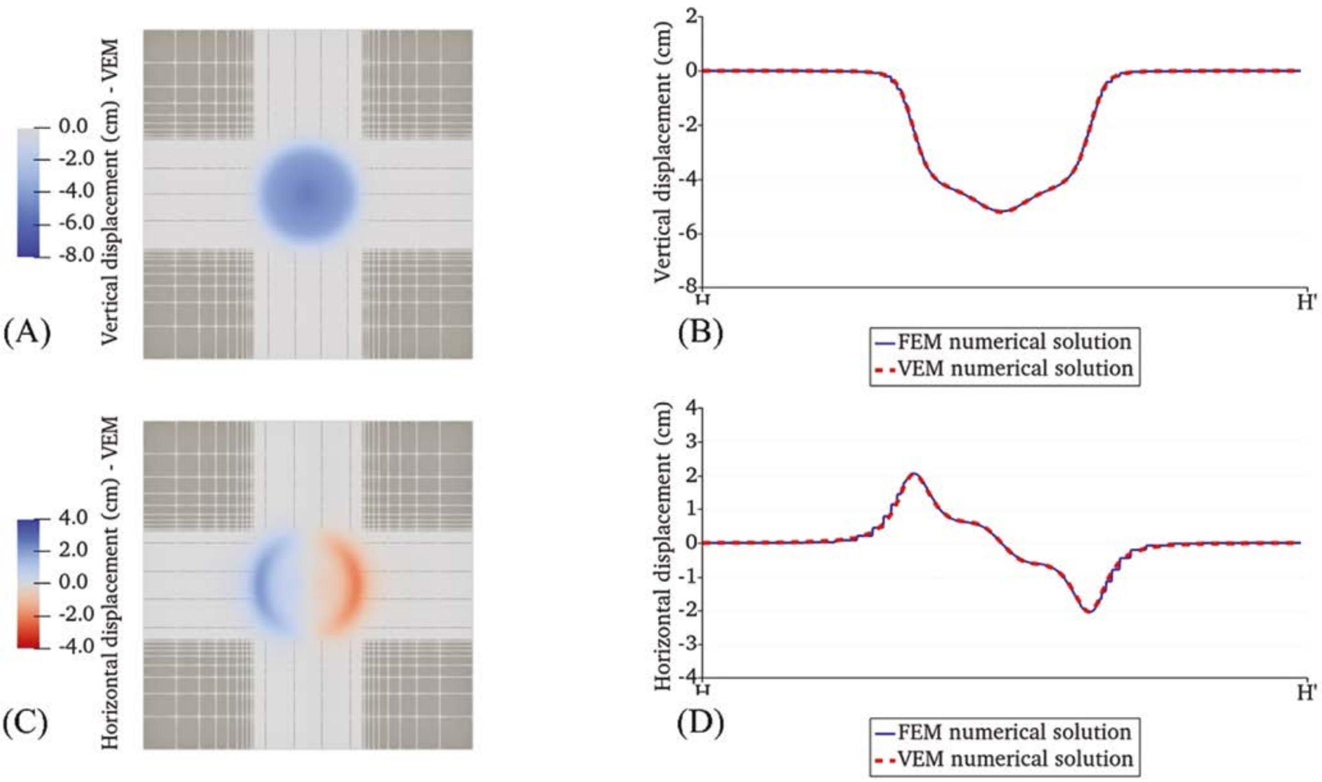

Fig. 6 – **End of injection cycle – timestep** t6 – Vertical displacement: (A) map of the VEM results at the sea floor and (B) comparison between the VEM and FEM results along HH'. Horizontal displacement: (C) map of the VEM results at the sea floor and (D) comparison between the VEM and FEM results along HH'.

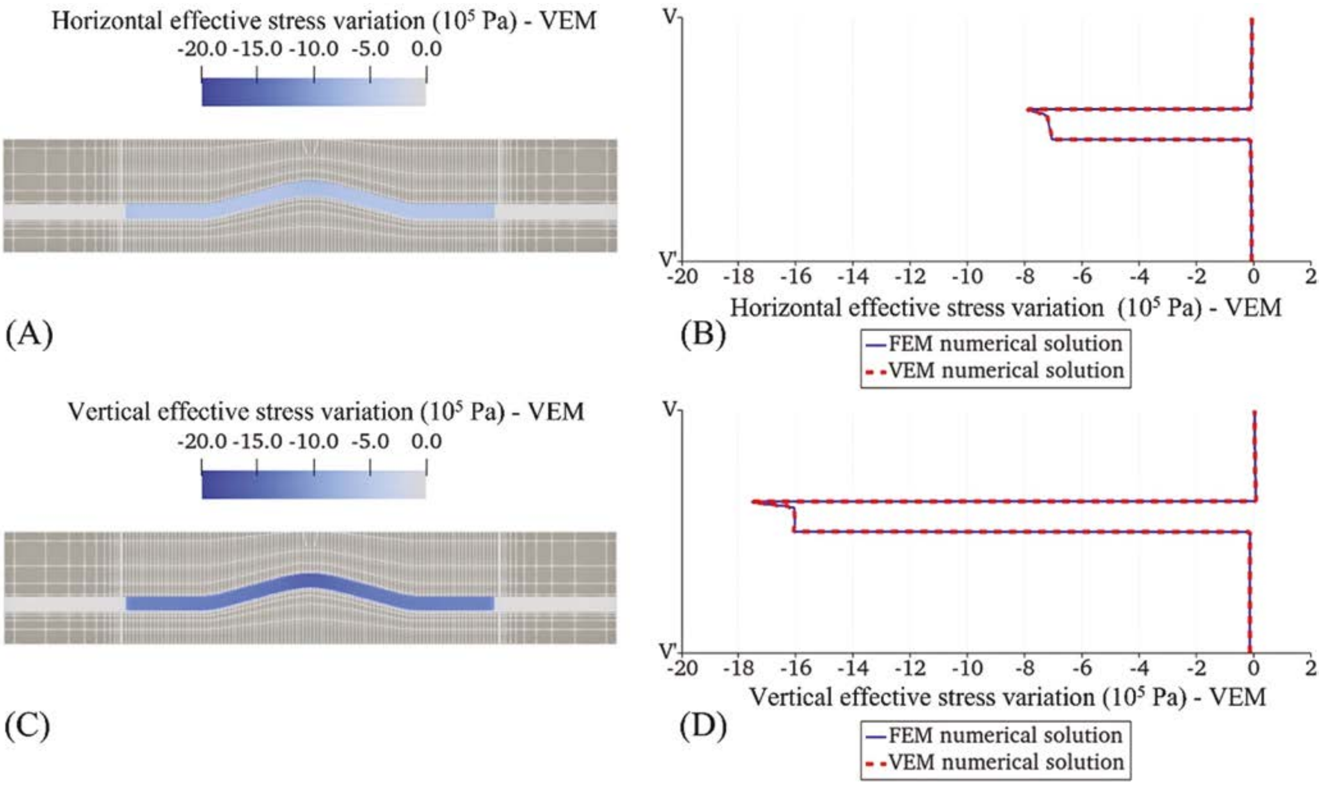

Fig. 7 – **End of injection cycle – timestep** t6 – Variation of the horizontal effective stress: (A) distribution of the VEM results along a vertical section throughout the reservoir and (B) comparison between the VEM and FEM results along VV'. Variation of the vertical effective stress: (C) distribution of the VEM results along a vertical section throughout the reservoir and (B) comparison between the VEM and FEM results along VV'.

In all the illustrated cases, a very satisfactory agreement between the VEM and FEM solvers is observed. Although the curvature of the present anticline results in non-planar cells at the reservoir level prompting a possible source of errors, VEM accurately reproduces the solution with negligible discrepancy.

6. Conclusions

The paper presents the validation of a Virtual Element Method code performed on a realistic case study representing a gas reservoir in the Italian Adriatic offshore. The code has been recently developed as part of a wider research project involving multi-disciplinary competences and it applies the Virtual Element Method in the elastic domain to calculate the response of stress-strain fields due to pore pressure variation induced by hydrocarbon production and/or storage operations.

According to the 3D multi-disciplinary modelling approach, the pore pressure evolution in a geological representative grid induced by the primary gas production and subsequent storage conversion was simulated via a multiphase flow software. The effects of the forcing function (i.e. pressure variation) in terms of stress-strain evolution is then calculated by a reference FEM approach (via a commercial software) and by the VEM code. The comparison was developed in terms of effective vertical and horizontal stress variations along a representative vertical segment, and of induced sea floor displacements, both vertically and horizontally, along a representative horizontal segment. The results show an optimum correspondence between the two approaches.

The present work represents the first important step in the evolution of the code toward a holistic approach which will be able to address rigorously the different physics of the phenomenon under investigation. In the next future, different constitutive models will be implemented to properly address the most common stress-strain behaviors exercised by hydrocarbon reservoirs during fluid production/injection. Furthermore, the code will be tested in a more complex geological/structural environmental involving also faults.

References

Ahmad, B., Alsaedi, A., Brezzi, F., Marini, L.D., Russo, A., (2013). Equivalent projectors for virtual element methods. *Computers & Mathematics with Applications*, *66*(3), 376-391. https://doi.org/10.1016/j.camwa.2013.05.015

Andersen, O., Nilsen, H.M., Raynaud, X., (2017a). *Coupled Geomechanics and Flow Simulation on Corner-Point and Polyhedral Grids*. D031S010R004. https://doi.org/10.2118/182690-MS

Andersen, O., Nilsen, H.M., Raynaud, X., (2017b). Virtual element method for geomechanical simulations of reservoir models. *Computational Geosciences*. https://doi.org/10.1007/s10596-017-9636-1

Beirão da Veiga, L., Brezzi, F., Cangiani, A., G, M., Marini, L.D., Russo, A., (2013). Basic principles of virtual element methods. *Mathematical Models and Methods in Applied Sciences*, *23*(01), 199-214. https://doi.org/10.1142/S0218202512500492

Beirão da Veiga, L., Brezzi, F., Marini, L.D., Russo, A., (2014). The Hitchhiker's Guide to the Virtual Element Method. *Mathematical Models and Methods in Applied Sciences*, *24*(08), 1541-1573. https://doi.org/10.1142/S021820251440003X

Beirão da Veiga, L., Brezzi, F., Marini, L.D., Russo, A., (2016a). Virtual Element Implementation for General Elliptic Equations. In G.R. Barrenechea, F. Brezzi, A. Cangiani, E.H. Georgoulis (A c. Di), *Building Bridges: Connections and Challenges in Modern Approaches to Numerical Partial Differential Equations* (pagg. 39-71). Springer International Publishing. https://doi.org/10.1007/978-3-319-41640-3_2

Beirão da Veiga, L., Brezzi, F., Marini, L.D., Russo, A., (2016b). Virtual Element Method for general second-order elliptic problems on polygonal meshes. *Mathematical Models and Methods in Applied Sciences*, *26*(04), 729-750. https://doi.org/10.1142/S0218202516500160

Beirão da Veiga, L., Dassi, F., Russo, A., (2017). High-order Virtual Element Method on polyhedral meshes. *Computers & Mathematics with Applications*. https://doi.org/10.1016/j.camwa.2017.03.021

Beirão da Veiga, L., Brezzi, F., Marini, L.D., (2013). Virtual Elements for Linear Elasticity Problems. *SIAM Journal on Numerical Analysis*, *51*(2), 794-812. https://doi.org/10.1137/120874746

Beirão da Veiga, L., Lovadina, C., Mora, D., (2015). A Virtual Element Method for elastic and inelastic problems on polytope meshes. *Computer Methods in Applied Mechanics and Engineering*, *295*, 327-346. https://doi.org/10.1016/j.cma.2015.07.013

Benedetto, M.F., Caggiano, A., Etse, G., (2018). Virtual elements and zero thickness interface-based approach for fracture analysis of heterogeneous materials. *Computer Methods in Applied Mechanics and Engineering*, *338*, 41-67. https://doi.org/10.1016/j.cma.2018.04.001

Benetatos, C., Codegone, G., Deangeli, C., Giani, G.P., Gotta, A., Marzano, F., Rocca, V., Verga, F., (2017). Guidelines for the study of subsidence triggered by hydrocarbon production. *Geoingegneria Ambientale e Mineraria*, *152*(3), 85-96.

Benetatos, C., Codegone, G., Ferraro, C., Mantegazzi, A., Rocca, V., Tango, G., Trillo, F., (2020). Multidisciplinary Analysis of Ground Movements: An Underground Gas Storage Case

Study. *Remote Sensing*, *12*(21). https://doi.org/10.3390/rs12213487

Berrone, S., Borio, A., D'Auria, A., (2021). Refinement strategies for polygonal meshes applied to adaptive VEM discretization. *Finite Elements in Analysis and Design*, *186*, 103502. https://doi.org/10.1016/j.finel.2020.103502

Berrone, S., Borio, A., D'Auria, A., Scialò, S., Vicini, F., (2021). A robust VEM-based approach for flow simulations in poro-fractured media. *Mathematical Models and Methods in Applied Sciences*, *31*(14), 2855-2885. https://doi.org/10.1142/S0218202521500639

Bocchini, S., Castro, C., Cocuzza, M., Ferrero, S., Latini, G., Martis, A., Pirri, F., Scaltrito, L., Rocca, V., Verga, F., Viberti, D., (2017). The Virtuous CO2 Circle or the Three Cs: Capture, Cache, and Convert. *Journal of Nanomaterials*, *2017*, 6594151. https://doi.org/10.1155/2017/6594151

Codegone, G., Rocca, V., Verga, F., Coti, C., (2016). Subsidence Modeling Validation Through Back Analysis for an Italian Gas Storage Field. *Geotechnical and Geological Engineering*, *34*(6), 1749-1763. https://doi.org/10.1007/s10706-016-9986-9

Coti, C., Rocca, V., Sacchi, Q., (2018). Pseudo-Elastic Response of Gas Bearing Clastic Formations: An Italian Case Study. *Energies*, *11*(9). https://doi.org/10.3390/en11092488

Deangeli, C., Cardu, M., Martinelli, D., (2021). Analysis of the Stability of Openings Excavated in Anisotropic Rocks. In M. Barla, A. Di Donna, D. Sterpi (A c. Di), *Challenges and Innovations in Geomechanics* (pagg. 361-368). Springer International Publishing. https://doi.org/10.1007/978-3-030-64518-2_43

Deangeli, C., Omwanghe, O.O., (2018). Prediction of Mud Pressures for the Stability of Wellbores Drilled in Transversely Isotropic Rocks. *Energies*, *11*(8). https://doi.org/10.3390/en11081944

DIANA FEA (2021). *DIANA Finite Element Analysis*. https://dianafea.com/

Ferronato, M., Castelletto, N., Gambolati, G., Janna, C., Teatini, P., (2013). II cycle compressibility from satellite measurements. *Géotechnique*, *63*(6), 479-486. https://doi.org/10.1680/geot.11.P.149

Gain, A.L., Talischi, C., Paulino, G.H., (2014). On the Virtual Element Method for three-dimensional linear elasticity problems on arbitrary polyhedral meshes. *Computer Methods in Applied Mechanics and Engineering*, *282*, 132-160. https://doi.org/10.1016/j.cma.2014.05.005

Jing, L., Hudson, J.A., (2002). Numerical methods in rock mechanics. *Numerical Methods in Rock Mechanics*, *39*(4), 409-427. https://doi.org/10.1016/S1365-1609(02)00065-5

Lipnikov, K., Manzini, G., Shashkov, M., (2014). Mimetic finite difference method. *Physics-compatible numerical methods*, *257*, 1163-1227. https://doi.org/10.1016/j.jcp.2013.07.031

Marzano, F., Pregliasco, M., Rocca, V., (2019). Experimental characterization of the deformation behavior of a gas-bearing clastic formation: Soft or hard rocks? A case study. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, *6*(1), 10. https://doi.org/10.1007/s40948-019-00130-3

Musso, G., Volonté, G., Gemelli, F., Corradi, A., Nguyen, S.K., Lancellotta, R., Brignoli, M., Mantica, S., (2021). Evaluating the subsidence above gas reservoirs with an elasto-visco-plastic constitutive law. Laboratory evidences and case histories. *Geomechanics for Energy and the Environment*, *28*, 100246. https://doi.org/10.1016/j.gete.2021.100246

Parkash, D., Deangeli, C., (2019). *Wellbore Stability Analysis in Anisotropic Shale Formations*. SPE-201183-MS. https://doi.org/10.2118/201183-MS

Rocca, V., Cannata, A., Gotta, A., (2019). A critical assessment of the reliability of predicting subsidence phenomena induced by hydrocarbon production. *Geomechanics for Energy and the Environment*, *20*, 100129. https://doi.org/10.1016/j.gete.2019.100129

Saad, Y., (2003). *Iterative Methods for Sparse Linear Systems*. Society for Industrial and Applied Mathematics. https://doi.org/10.1137/1.9780898718003

Schlumberger (2020). *VISAGE*. /products/visage

Teatini, P., Castelletto, N., Ferronato, M., Gambolati, G., Janna, C., Cairo, E., Marzorati, D., Colombo, D., Ferretti, A., Bagliani, A., Bottazzi, F., (2011). Geomechanical response to seasonal gas storage in depleted reservoirs: A case study in the Po River basin, Italy. *Journal of Geophysical Research: Earth Surface*, *116*(F2). https://doi.org/10.1029/2010JF001793

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Conflicts of interest

The authors declare no conflict of interest