ENHANCED GEOTHERMAL SYSTEM GEOPRESSURIZED WITH CO₂ IN DEEP SALINE AQUIFERS

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Abstract: Through analytical modeling of fluid flow and geomechanical phenomena is here given birth to an energy system that integrates CCS and geothermal energy. It uses the injection of CO_2 in deep saline aquifers to generate a range of pressures that facilitates the upgrade of geothermal fluids from geological formations that constitute the *caprock* or any porous aquifers overlaid with the aquifer reservoir. the uptake of these fluids promotes dissipate excess pressure and at the same time the settlement of *primary consolidation* of the formations overlying the aquifer subjected to the vertical elastic displacement. Preserves itself, in this way, the balance of the system and shows how the CCS can have a double purpose: on the one hand reduce the emission of CO_2 into the atmosphere, and the other end to provide a energy contribution with the exploitation of a source of renewable energy.

Keywords: *caprock, u neutral pressure, consolidation pressure*, *primary consolidation, fracking.*

1. INTRODUCTION

In this paper we discussed the contribution that the Carbon Capture and Storage (CCS) can make to the development of an integrated energy system doubly careful to safeguard the environment. It is conceived for the combined use of geothermal fluids as a source of energy as a result of storage of CO_2 in the deep layers in place of issue of the same gas in the atmosphere. Because this system can find real application it is necessary that some structural-geological conditions are met. It is essential that there is the presence of an aquifer saturated permeable to porosity, which represents the complex hydrogeological suitable to contain CO_2, buffered at the top by a waterproof geological formation called *caprock*, extended up to the surface (land surface) or alternating layers less permeable or secondary saturated aquifer with the role reservoirs of geothermal fluids. A schematic and simplifying (in nature the structural conditions can be much more complex) is that of Figures 1 and 2.
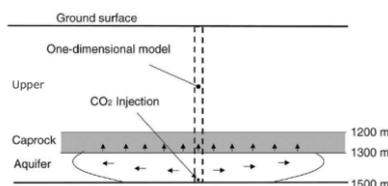

Fig.1- One-dimensional model simplified of CO_2 injection in an *aquifer-caprock* system (from ERSE [2010]).
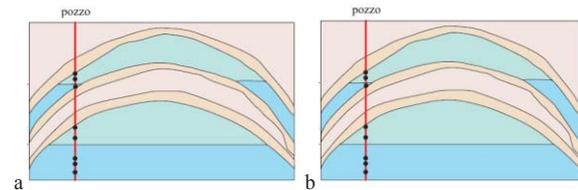

Fig.2 – a. Lenticular reservoir; b. Reservoirs separated by a single regional aquifer (Volume I / Exploration, Production and Transportation Encyclopedia Treccani 2008).

From the results of the geomechanical and fluid dynamic simulations performed by - Cocozza et al., 2013 - it can be said as the injection of CO_2 in deep saline aquifers to generate a pressure field throughout the aquifer, without exclusion of that part of the same aquifer is not yet affected by the advance of the CO_2 plume. The interstitial overpressure generated together with the elastic deformation induced in the aquifer reservoir, is transmitted as a uniformly distributed load at the interface between the aquifer and *caprock*, causing in the fluid contained in the geological layers overlying the aquifer a range of pressures varied with distance from the point of load application (Fig. 1). Because of the hydrogeological properties of these impermeable formations, characterized by a very low value of permeability of the order of 10^{-15}-10^{-17} m², this overpressure is not quickly dissipates over time. The low transmissivity, i.e. the reduced tendency to dissipation of overpressure, causes the vertical displacement of the *aquifer –caprock* system, result of the elastic deformation of the aquifer subject to the pressure of injection of CO_2. The direct uptake of fluids, then, is necessary so that another way to banish the overpressure generated by the injection of CO_2 with the result to preserve the structural balance of the *aquifer-caprock*. In the presence of an impermeable layer as the *caprock*, the fluid contained in it is stored in the small fractures and in the pores of very small dimensions. To improve the hydraulic conductivity and allow the extraction of fluids we proceed to the generation of fractures of long and narrow that increase the draining surface and penetrate deeply into the geothermal reservoir, through the technique of *fracking*. From this point of view the *caprock* is comparable to an EGS (Enhanced Geothermal System) in which geothermal energy is defined as a complex of competent rocks buried, having natural little or almost nothing permeability, located in areas with or without regional thermal anomalies, at a temperature depends only on depth. In this respect, many projects capture and sequestration of CO_2 are now struggling to take off, would be much more attractive in an economy focused on

minimizing costs and benefits. Carbon capture and storage of CO_2, by itself consuming processes, when combined with geothermal purposes may constitute, in favorable geological conditions, an excellent opportunity for development in the presence of high levels of atmospheric emissions for countries (such as those in the West) prevented immediately to radically change their business model and intend to start gradually towards a new scenario of eco-friendly development. They may even take advantage of in the reverse direction, the same production processes (poly steel, cement, refineries, power plants, etc ...) who for years have produced environmental impacts decided and now seemingly insurmountable.

2. DISTRIBUTION OF *NEUTRAL OVERPRESSURE* IN THE *CAPROCK*

The flow of CO_2 into the aquifer reservoir (Fig. 1) induces an applied load (pressure + pore deformation of the soil skeleton) [Cocozza et al. 2013] at time $t=0$ and generates a distribution of *u neutral pressure* in the fluid that saturates the *caprock* besides a distribution of stress on the solid skeleton. For *u neutral pressure* means the water pressure in the pores and the neutral overpressure is the increase of this pressure. The overhead per unit area that causes the *primary consolidation* is called *consolidation pressure*. In general for *primary consolidation* is the phenomenon of gradual decrease of water content under a constant load [Terzaghi-Peck 1967]. The instant in which it is applied, this pressure is almost entirely supported interstitial water, for which, at the beginning of the process, there is an overpressure in the water almost equal to the entire consolidation pressure. With the passage of time the pressure in the water decreases, and instead increases the mean effective pressure on the layer. After a long period of time, the excess pressure hydrostatic pressure will reverse and the entire consolidation becomes an actual stress transmitted from grain to grain [Viggiani 1967].

The solution that best approximates the distribution of overpressure in the geothermal reservoir is given by the vertical load variable with a triangular law on the strip.

With reference to Figure 5, the load acting on the line of infinitesimal thickness $d\xi$ and distance ξ from the discharge edge of the strip applies $p(\xi/B)d\xi$; it induces in a generic point of coordinates x, z, an overpressure that is, for the more general case of a load uniformly distributed on a straight line:

$$du = \frac{pz}{\pi B}\frac{\xi d\xi}{z^2+(x-\xi)^2} \qquad (1)$$

The neutral overpressure induced by the acting load on the entire strip will be worth then:

$$u = \int_0^B du = -\frac{px}{B\pi}\left(arctg\frac{x}{z} - arctg\frac{x-B}{z}\right) + \\ + \frac{pz}{2B\pi}ln\frac{z^2+(x-B)^2}{z^2+x^2} \qquad (2)$$
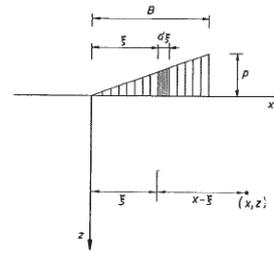

Fig.3- Variable load with vertical triangular law on a strip (Viggiani 1967).

The porosity of the rock will prove to be higher than the value that we expect for the given depth of arrangement, since the sediments are subjected to effective pressures less than those which would be supported in the presence of normal pressures (you may assign the conditions of a soil subconsolidated) and consequently exhibit different physical and mechanical properties compared to the same normally consolidated soils; clays, also tend to expand in the well, where they are not properly contrasted by a sufficient pressure of the drilling mud. In secondary aquifer places above the *caprock*, before the injection of CO_2 in the aquifer reservoir-below, the pressure of the fluid contained in it is close to or equal to the hydrostatic. Is, however, in particular geological conditions, the fluids are in a state of abnormal pressure, or at a lower pressure (negative pressure) or above (pressure) to the hydrostatic.

The parameters that influence the pore pressure are in particular the load applied, function of the flow rate of CO_2 injection in the aquifer reservoir and at the same time the hydrogeological parameters essential to the determination of the storage coefficient S_s and therefore the radius of influence R of the pressure cone.

3. TECHNIQUES TO IMPROVE THE HYDRAULIC CONDUCTIVITY OF THE *CAPROCK*

Improve the transmissivity of low permeability formations (*caprock*) means to increase the productivity of wells pumping of geothermal fluids. In fact, by the experience of the fields for the extraction of shale gas, the cultivation of a field with non-conventional vertical wells involves a considerable number of perforations in function of the production.

In order to minimize costs and improve productivity, the choice of wells with horizontal development is preferred in the case of CO_2 injection, since the advance of the plume from the injection well geo pressurizes the *caprock* with distance increasing from the well injection.

So to avoid a rapid depletion of the rate flow of a well to vertical development to increase the pressure in the aquifer (*caprock*) (remember that the flow of CO_2 is considered radial from the point of injection), the choice of the work of uptake should fall towards a well horizontal development with delivery to the maximum distance from the point of injection of CO_2. Together with the improvement of the permeability by *fracking* the interstitial fluids would reach with flow conspicuous and constant advancing of geo

pressurization. The technology of *fracking* (fig.4) is to create fractures in the rock through the injection of high pressure water. The number of artificial fractures, their length and their positioning within the layer (vertical or horizontal) depends on the characteristics of the geological formation. These characteristics have an impact on the length of the artificial fractures, on the spacing of the wells (vertical wells have a density greater than the horizontal wells) and on water consumption. The geo pressurization and *fracking* promote the upgrade "spontaneous" of these geothermal fluids with considerable effect on energy costs of pumping.
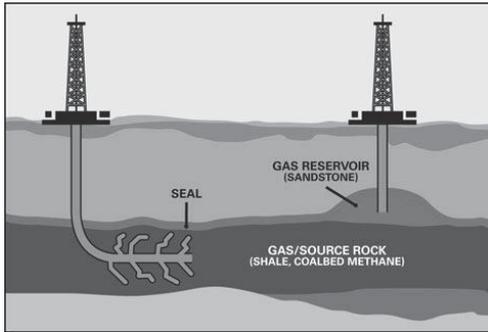

Fig.4 - Schematic representation of the technology of *fracking* used to extract gas from shale and domes of rocks containing free gas in formations extending substantially longitudinal and with horizontal wells.

This upgrade can be calculated by solving the equation for the mechanical energy (3) that describes the flow of the fluid in a well of diameter D as a function of upgrade Δz:

$$\Delta z = \frac{p_1 - p_2}{g\rho} + \frac{S^2}{2g}(Q_1^2 - Q_2^2) + \frac{2 f_f S^2 Q_2^2 \, dl}{D \, g \, \rho} \quad (3)$$

Where ρ is the density of the fluid, S is the areal section of the well, g the acceleration of gravity, $\Delta p = p_1 - p_2$ is the pressure drop on an infinitesimal distance dl of the well, f_f is the friction factor of Fanning, Q_1 and Q_2 the flows respectively to the pressure values p_1 and p_2 generated by geo pressurization in the geothermal reservoir. The following are diagrams of simulation for vertical and horizontal development wells with significant difference in the values of upgrade (fig.5-6).
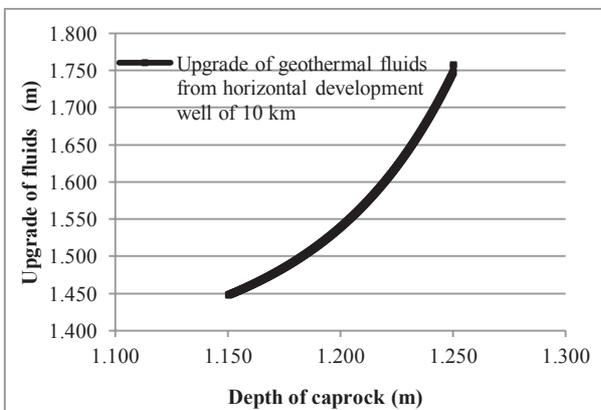

Fig. 5 - Upgrade of interstitial fluid from a well with a horizontal development allocation in the *caprock* and function of depth following the injection of CO_2 for a year.
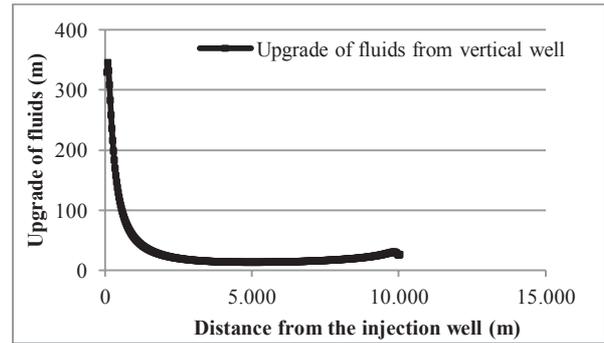

Fig.6 - Upgrade of interstitial fluid from a well with a vertical development allocation in the *caprock* and in function of the distance from the well of CO_2 for a year of injection in the aquifer below.

4. DECREASE OF EXPANSION OF THE *CAPROCK* FOR PUMPING INTERSTITIAL FLUID

With the solution of Cooper to Jacob [1946] (4) it is possible to determine the decrease of pressure to a confined aquifer subjected to a constant pumping and calculate both the expansion in the absence of pumping, subject only to the interstitial or pore pressure, and both decrease of expansion or settlement due to decrease of pressure to effect pumping.

$$\Delta p_w = \frac{Q_0 \mu_w}{4\pi k d} ln\left(\frac{2{,}25 k \rho_w g t}{\mu_w r^2 S_s}\right) \quad (4)$$

For expansion of the *caprock*, the storage coefficient S_s, is the availability of fluids present in the *caprock*, but also the state of stress and the course of the tensions suffered by the formation in its geological history. One of the most important parameters that defines the state of stress is the coefficient of Skempton that can be determined experimentally by means of undrained triaxial tests.

The negative values of A for the heavily overconsolidated clays (it is said of those clay soils that have been subjected to a pressure greater than the effective lithostatic load current) is the manifestation of the same physical phenomenon for which the path of effective stress intersects, what of the total stress, a phenomenon that, in drained conditions, it is also the base of the dilatant behavior of these materials. From here, it is of considerable importance to know the geological history, in terms of stress, of land that make up the site to predict the behavior under the action of applied loads.
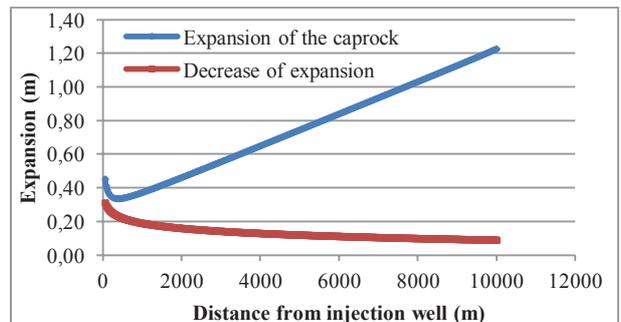

Fig.6 - Expansion of the *caprock* in the absence of pumping and pumping of fluids after a year of CO2 injection.

Tab.1 - Average values of the coefficient A Skempton
for some clays

Type of soil	*A*
Normally loaded clay	0.5 : 1.0
Lightly overconsolidated clay	0 : 0.5
Strongly overconsolidated clay	-0.5 : 0

5. CONCLUSIONS

The model developed here demonstrates that the fluids in pressure in the *caprock* and aquifers secondary superimposed can be received, inducing, for the reasons deriving from the theory of consolidation of Terzaghi (1946), a failure of the *caprock* (understood as the decrease of expansion) if the fluids are captured in this formation or secondary aquifers but if these are to be affected by pumping. In the first case, the settlement of the *caprock* will absorb it as a "inelastic mattress" for the cohesive nature of the land that composes it, the vertical displacement of "aquifer-reservoir" (Cocozza et al.2013) due to the decrease of expansion suffered as a result of pumping, while in the second case, the settlement or decrease in the expansion of the aquifer saturated porous overlapping the aquifer-tank and the *caprock* to absorb as a "elastic mattress" the vertical displacement.

Thanks to the behavior of these materials and to the concept that in order to preserve the balance of the system, if you inject something into the ground it is necessary that something else is extracted, comes the opportunity to develop this energy system combined. Certainly its application can't be separated from experimental tests, to accomplish even on a small scale, in order to simulate the interactions between the various types of soil are characterized by very different hydrogeological parameters.

Hydrogeological parameters, which are known to be critical in determining the productivity of the geothermal reservoir, possibly to make it more supportive interventions with *fracking* that even if considered dangerous to the possible impact on the environment and human health, can be applied with appropriate recommendations and controls in accordance with the European regulatory framework.

Regulatory framework evolving due to the continually increasing use of this technology in areas such as the extraction of gas and oil shale.

List of symbols

A Skempton coefficient [-]
B Length of the strip [m]
d Thickness of the formation [m]
D Diameter of the well [m]
dl Infinitesimal distance [m]
du Increase of neutral pressure [Pa]
$d\xi$ Line of infinitesimal thickness [m]
f_f Friction factor of Fanning [-]
g Acceleration of gravity [m/s^2]

k Coefficient of permeability [m^2]
p Pressure value at the point of coordinates (x, z) [Pa]
p_1 Pressure value generated by geo pressurization [Pa]
p_2 Pressure value generated by geo pressurization [Pa]
Q_0 Volumetric flow rate [m^3/s]
Q_1 Volumetric flow rate to the pressure value p_1 [m^3/s]
Q_2 Volumetric flow rate to the pressure value p_2 [m^3/s]
r Radial distance from the injection well [m]
R Radius of influence of the pressure cone [m]
S Areal section of the well [m^2]
S_s Specific storage coefficient [1/m]
t Time [sec]
u Neutral pressure [Pa]
x x-axis of point of measurement of the overpressure [m]
z z-axis of point of measurement of the overpressure [m]
Δp Pressure drop [Pa]
Δp_w Decrease in water neutral pressure [Pa]
Δz Upgrade of the fluids in geothermal reservoir [m]
μ Viscosity of the interstitial fluid [Pa*s]
ξ distance from the discharge edge of the strip [m]
ρ Density of the interstitial fluid [kg/m^3]

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