In a number of industrial processes aimed at producing energy, geomechanics plays a significant role. Although not exclusive, the topics considered here appear to circle about two central issues. On the scientific side, emphasis is laid on thermo-hydro-chemo-mechanical couplings, including multiphase flows, phase changes and evolution of a micro-fracture network. While mechanics and geomechanics play a central role, couplings are essential ingredients in most, if not all, the issues addressed.

On the industrial side, several topics center on energy production and on natural phenomena in the oceans. As far as energy resources are concerned, the oceans are already, and the trend will continue for some period, the next frontier. According to a 2008 USGS assessment, about 25% of the world conventional resources in oil and natural gas may be located in the seafloor of the Arctic region. These resources become more and more accessible as climate change opens maritime routes. Environmental issues are considerable. Burying one's head in the sand is not a policy. The challenges should be considered, so that policy-makers may take decisions on the sustainable development of marine resources based on technological and scientific arguments.

Electricity in France is at 80% of nuclear origin. As far as green house gas emissions are concerned, this situation is way more confortable than that of most other industrial countries. In 2010, electricity production in Germany is based on 55% on coal and gas against 7% in France. The resulting emissions of CO2 per kWh amount to 50 g in France versus 600 g in Germany.

Still, putting aside the nuclear risk, this ominipotence of the nuclear energy has created a sort of Dutch disease. The need to discover and develop alternative energies has been felt less urgent than in other countries whose electricity production is, and will be for the next 30 years, based on fossile resources. Even with the most optimistic forecasts, the production of electricity in the USA in 2030 will be based on coal and gas for more than 60% and on so-called renewable energies for less than 25%.

Whether they regard the issue of energy production with a Malthusian or Cornucopian eye, Occidental societies and goverments alike agree that the available fossile resouces should be exploited more efficiently and with more attention to the environmental consequences.

These two concerns are an Ariadne's thread in the research issues touched here.

Contents

The notes below provide a short and informal description of each of these items.

Methane hydrates: production issues and stability of the seafloor

Methane hydrates are presently viewed as a potential energy source for the 21st century as a large amount of methane gas is trapped in seafloor reservoirs. Hydrates form under specific thermodynamic conditions, namely high pressures (a few MPa) and low temperatures (0 to 5°C), below deep oceanic sediments, and in the pergelisol of polar regions. There are two main modes of hydrate formation : biogenic methane is a by-product of bacterial ingestion, while thermogenic methane results from the transformation of organic matter over long periods of time due to heat and pressure. Hydrates are found in nodules or in pores of sediments. Although the gas is not chemically bound to water, it occupies lattice positions in the water structure, and gas hydrates appear as solid crystalline compounds, looking like ice. The quantification of the actual amount of existing and exploitable hydrates is currently under way.

These gas reservoirs are of interest for two main reasons :

1. they are seen as containing a huge source of energy, and
2. the leakage of gas may affect the marine environment and subsequently contribute to air pollution and global warming (methane is twenty three times more effective at trapping greenhouse gases than carbon dioxide) : in fact, releases of methane have been hypothesized as potential driving sources/consequences of past climate changes.

In the case of the Nankai Trough located 50km off the eastern coast of Japan, methane hydrates are buried at a water depth of about 1000 to 1500 m. The volume fraction of gas is up to 20% of the sediments it is trapped in. The amount of gas in seafloor around Japan alone is estimated to provide energy equivalent to 90 years based on its current consumption. Production is a major technological challenge. Actually the zone which has been the most actively explored is the Mackenzie Delta, in the Arctic zone, North-West Canada.

There are several problems to be solved during the production of natural gas from hydrate bearing sediments. These mainly relate to (1) the search and exploration of high quality deposits containing methane hydrates, (2) investigation of methods for producing the gas, and (3) consequences of the effects of gas production on the environment. The third item includes ground deformation due to the extraction of methane hydrate and the leakage of gas. When gas is extracted from the marine sediments, extensive subsurface deformations may lead to seabed catastrophic slides, and ensuing tsunamis.

Several production schemes have been proposed to extract the gas from hydrates, namely, (1) thermal injection of hot water destabilizes the hydrates, (2) depressurization causes the hydrates to dissociate, and (3) chemical inhibitors shift the dissociation curve in a pressure-temperature plane to lower pressure. There are many uncertainties in these production processes, especially related to the subsurface deformation and failure caused by gas dissociation. A comprehensive constitutive model coupling thermal flow and phase change, fluid seepage and gas diffusion, and mechanical aspects (de-cementation, deformation and failure) should be developed. These difficulties do not deter the spirit of enterprise of oil companies, and an optimistic win-win method consisting in displacing methane by injection and sequestration of carbon dioxide is in the air. A technique would consist in delivering a micro-emulsion of CO_2 and water at temperature higher than the stability point of methane hydrate but lower than that of carbon dioxide hydrate. Gas exchange techniques of the same flavor are developed for enhanced recovery of oil, conventional natural gas, and coal-bed methane.

Research topics

1. Mechanics of partially saturated soils
2. Transport: thermal diffusion, fluid and gas flows
3. Phase change, latent heat, volume change
4. Mechanical couplings associated with phase change and de-cementation

CO_2 sequestration: simulations of injection and long term stability of the storage

The pre-industrial concentration of carbon dioxide CO_2 in atmosphere is estimated to about 280 ppm (0.028% CO_2), its current concentration is about 390 ppm, and a widely accepted critical threshold for climate change is 450 ppm. Perturbations of the genuine cycle of CO_2 is thought to be due to industrial activities, including burning of fossil fuels, coal, oil and gas, in power plants, transportation, individual and collective heating … Increase in concentration of CO_2 in the atmosphere during the industrial period implies that the heat capacity of the atmosphere to increases. The latter captures more heat from sun, increases its temperature, and by the same token, that of earth. However, increase of temperature in earth is bound to perturb considerably the genuine equilibrium between geosphere, biosphere and oceans, in terms of energies and of gas exchanges.

Out of the 1300 Gtons of CO_2 due to human activities in the last 200 years, 500 Gt have been dissolved in water. Now, note the important feature that CO_2 is an acid gas, $CO_2 + H_2O \Rightarrow H^+ + HCO_3^-$.
While there have been no large scale experiments of active injection of CO_2 into the ocean, the *acidification of the oceans* is estimated to a pH decrease of about 0.1.

Ideally, one might think to reduce the activities that produce CO_2. However, in view of availability and cost of fossile energy sources, this is not a realistic target. Developed countries, and utmost developing countries, will use the cheapest energy available, namely coal-borne. The fact that the latter will become extinct will constitute an incentive to imagine, develop, and produce new forms of energies that are cleaner. Still, the attitude of governmental bodies is currently, and temporarily, to cure the undesirable consequences, that is, to cope with the CO_2 emissions along the following schemes: (1) reduce the emission to the atmosphere of CO_2 by storing in the ground, using for example the natural reservoirs discovered in the 60's in southern France; (2) fund fundamental and industrial research to develop cleaner energy sources, in view of reaching in the long range a sustainable energy system.

Gas sequestration includes a number of complex operations: (1) capture of CO_2 at the exit of power plants, refineries, coal-burning plants; (2) transport to a storage unit; (3) injection into a suitable geological formation for long-term storage. The offshore Sleipner site in Norway illustrates the process. The natural gas extracted there from a deep layer contains a percentage of CO_2. Since the percentage is higher than the standard allowed in commercial use, CO_2 is separated from the natural gas, and re-injected into a sandy aquifer at a rate of 1Mt/year. Other demonstration projects have been developed at Weyburn, Canada, at Salah, Algeria, and in the offshore site K12-B, the Netherlands.

Appropriate on-shore storage locations include

(1) depleted gas and oil fields, already known during the exploitation phase, and featuring (a) sufficient porosity, permeability, and storage capacity; (b) an overlying impermeable cap rock preventing upward migration of gas; (c) a depth larger than 800 m with pressure and temperature implying a compressed fluid phase; (d) no link with drinking water reservoirs.
(2) deep saline aquifers, with large storage capacities, from 1 to 4km deep, 100 to 400 g of salt/l against 35g/l for seawater, and 9 g/l for human blood;
(3) unmineable coal seams, with low permeability.

The potential fields are located in sedimentary basins, like the Parisian Basin, or the Southern Permian Basin from England to Poland. The estimated storage capacity in the North Sea is about 37 Gt of CO_2, which is about a yearly anthropic production.

CO_2 is sequestred under *supercritical conditions*. Under supercritical conditions, a substance behaves like a gas although it has the density of a fluid. For CO_2, the critical point is 31°C and 7.38 MPa, and its density in the supercritical conditions ranges around 600-800 kg/m3. As a matter of comparison, dry air has a density of 1.2041 kg/m^3 at 20 °C and 101.325 kPa.

The sustainability of the storage relies on mechanical and chemical issues. Clearly, the injection pressure should be larger than the reservoir pressure and smaller than the fracture pressures of the reservoir and cap rock. The injection process should avoid to re-activate existing faults, if any. Once injected, CO2 enters the pore space which is already filled with brine. A number of chemical and physical phenomena, with distinct characteristic times, take place that contribute to ensure the stability of the storage, namely, according to CO2 Geonet 09/2008: 1. structural trapping (fast process): since supercritical CO2 is still lighter than water, it tends to rise, until it encounters an impermeable cap rock; 2. residual trapping: small pores of the reservoir itself may trap CO2 preventing it to move upward; 3. dissolution trapping (slow process, years): dissolution of CO2 in the brine makes the mixture brine+dissolved CO2 heavier than brine. The mixture thus moves downwards. Actually due to the continuous injection of CO2, there is some sort of continuous mixing between fluids; 4. mineralization (very slow, centuries): supercritical CO2 and brine may react with rock, especially carbonate minerals, leading to mineral dissolution and/or precipitation, depending on pH. Typical estimations of the state of CO2 for the Sleipner reservoir are as follows: at injection, 100% is supercritical, after 10 years, 15% is dissolved, after 10 000 years, 95% is dissolved, 5% mineralized.

In conclusion, the various physical phenomena that take place in the reservoir may increase the stability of the storage. The main feature of a storage site is the presence of an efficient cap rock. Further chemical reactions of the rock around the injection well includes the dissolution of carbonates that increases of porosity, and storage capacity, but possible acidification and re-precipitation may lead to cementation, which decreases the permeability.

A potential threat is gas leakage either through fracture systems in cap rock and faults, or via the injection wells, the acidic environment created by carbon dioxide possibly corroding the cementitious sealings. Gas diffusion is a slow process while gas advection driven by pressure differential and fluid flow may be more dangerous.

Simulations of carbon dioxide injection should use a multiphase approach including the deformable solid rock, carbon dioxide and water in both liquid and gaseous phases, and sodium chloride. Chemistry and mechanics work hand in hand : phase changes and salt precipitation interact with the fluid pressure and skeleton strain. Stability of the cap rock involves again chemo-mechanical couplings, since the acid environment may attack carbonate rocks, and significantly decreases their mechanical properties. Salt precipitation/dissolution and rock compressibility may further alter the formation permeability.

A key issue with alternative energy sources lays in the technological difficulties associated with their storage. Storage of mixtures of gases in aquifers, especially hydrogen and carbon dioxide, is being envisaged. These mixtures undergo intense chemical reactions catalyzed by bacteria. The large diffusivity of hydrogen gives rise to a dynamic behavior whose evolution and stationarity are open issues.

Research topics

1. Simulation of carbon dioxide injection: chemo-mechanical interactions
2. Influence of the acid environment on the mechanical and transport properties of the cap rock
3. Sustainability of CO2 sequestration in the short range (induced seismicity) and long range (leakage)

Biotechnology for a cleaner environment and energy extraction: geomechanical issues

Soil stabilization is required in a number of geotechnical contexts, to mitigate liquefaction of sand, to compact reclaimed sites. In oil and gas extraction processes, boreholes in loosely cemented materials produce sands. Cement grouting or soil mixing techniques become inefficient when the volumes of soil to be treated are large. Biotechnological approaches aim at using bacteria as catalyzing agents to either precipitate or dissolve inorganic minerals. The bacterial activity is expected to modify both the mechanical and transport properties of the soils. They might occasionnally replace acidation to increase the permeability of tight gas reservoirs. Since the bacteria need to be transported beforehand, the approach is not suitable to fine grained soils. Perhaps, the growth of fungi might be used as a template as far as chemotaxis is concerned, while haptotactic properties are suspected to be different.

Here are three geomechanical instances where biotechnology is a promising tool.

1. Bioclogging, a technology to reduce permeability of geological formations and enhance the cap rock sealing of underground CO_2 storage sites.

Supercritical CO_2 is only slightly soluble in water, less dense and less viscous than the initial brine. Strategies to block, or limit, the upward migration through fractures or through the disturbed zone surrounding the boreholes are therefore to be addressed.

The idea is to inject, at a prescribed rate, bacteria of sub pore size and low viscosity nutrients. The process is expected to control the bacterial growth in space and time so that, over time, the mineralization contributes to clog the pore space of the cap rock of geological repositories, therefore limiting the potential leakage of CO_2 to the surface. The technique could be used to reduce the migration of heavy metals and other pollutants. By the same token, the mechanical properties of the rock are expected to be improved and the long term stability reached at a faster pace.

2. Bio-cementation to improve mechanical properties of soils

This very idea above has also been used recently by a team of Delft University and Deltares in a purely mechanical perspective to reinforce a soil. Here, the bacteria were injected first, followed by urea and calcium chloride. The bacteria were able to catalyze the hydrolysis of urea into ammonium and carbonate, and the latter precipitates in calcium carbonate crystals at grain contacts. In small scale tests, the soil, initially a sand, is reported to acquire the stiffness of sandstone. The steady state strength correlates with the calcium carbonate concentration, and, ideally, it might be controlled by the injected substrate concentration. In field tests, a main difficulty will be to ensure a homogeneous, or controlled, spreading of bacteria and nutrients to obtain the desired improvements of mechanical properties.

3. Accelerate underground conversion of coal to methane

Combustions of methane and coal release respectively 55 and 100 kg of CO_2 per GigaJoule. In order to decrease the emission of heat trapping gases, it would be therefore of interest to develop techniques that can accelerate the underground conversion of coal to methane. A biotechnological approach is being tested by Australian researchers. The mechanical issues accompanying this phase change are expected to be of the same flavor as those arising during the dissociation of methane hydrates, albeit over a longer time window.

Enhanced geothermal systems (EGS): efficiency and sustainability of stimulation methods

La recherche et l'exploitation de sources d'énergies renouvelables, alternatives aux énergies fossiles, sont motivées par des considérations pratiques (extinction de la resssource fossile), environnementales, politiques et sociétales.
Les deux formes principales de l'exploitation de ressources géothermiques entrent dans ce contexte. La géothermie à basse énergie exploite la chaleur du sous sol à faible profondeur, une vingtaine de mètres, et elle vise les chauffages urbain et collectif. La géothermie à haute énergie exploite la chaleur des roches, de température 200°C à 300°C, situées à plus grande profondeur, mille mètres et plus, le fluide extrait servant à produire de la vapeur qui active des turbines dont la rotation dans un champ magnétique engendre un courant électrique.

Cette dernière perspective constitue un problème scientifique alliant le génie civil (diffusion de fluides, fracturation et déformation de roches) et le génie mécanique et thermique.

Modéliser l'extraction de chaleur dans des sites géothermiques fait intervenir des aspects de mécanique des milieux continus, des phénomènes de diffusion et transfert de masse et de chaleur en milieux poreux saturés. Le processus consiste (a) à injecter un fluide dans un horizon rocheux, situé en profondeur et chargé en énergie, (b) à faire circuler ce fluide de sorte que sa faible température initiale s'élève progressivement lors de sa diffusion dans l'horizon rocheux, et (c) finalement à l'extraire à partir d'un puits positionné à un certaine distance horizontale du puits d'injection, de l'ordre du kilomètre. La chaleur récupérée est utilisée en surface par des échangeurs thermiques, soit pour chauffer des logements soit pour produire de l'électricité. Le fluide, une fois déchargé de son énergie, est ré-injecté. Une difficulté principale dans l'exploitation d'un site est d'obtenir une circulation rapide du fluide dans la roche sur une distance suffisante.

La stimulation de réservoirs géothermiques est expérimentée dans quelques sites instrumentés, Soultz-sous-Forêts en Alsace, Rosemanowes en Cornouailles, ainsi que dans quelques autres pays, Etats-Unis, Japon, Australie, Nouvelle Zélande … La production d'électricité atteint ou dépasse l000 MWe dans seulement 5 pays, Etats-Unis, Philippines, Mexique, Indonésie, Italie.

Les travaux de recherche actuels s'attachent à intégrer progressivement différents aspects concernant la modélisation mécanique, les écoulements et les transferts thermiques dans l'horizon rocheux considéré comme un milieu poreux à deux porosités, une porosité faisant office de réservoir d'énergie et la seconde assurant la diffusion du fluide. Ainsi, on peut considérer (1) un modèle mécanique à double porosité; (2) un modèle d'écoulement à double perméabilité (une perméabilité pour chaque porosité), incluant également un échange de masse entre les deux porosités; (3) une diffusion thermique dans la roche et dans le fluide, et des échanges thermiques entre matrice solide et fluides.

Le fluide à haute température réside dans la roche poreuse, dont la perméabilité est faible. La présence des fissures peut être naturelle. Il est cependant à craindre que, dans ce cas, le fluide chaud se soit échappé, à moins que la zone fissurée soit circonscrite par une formation imperméable aux flux hydrique et thermique. If faut donc s'attendre à devoir stimuler le réseau de fissures (4) par fracturation hydraulique ou (5) par voie chimique, cad acidification (dissolution des carbonates par fluides réactifs), ce qui engendre des processus couplés de diffusion-réaction-précipitation et déformation. Des tests sur des sites de référence ont cependant montré que, si la porosité augmente à proximité du puits d'injection, elle diminue aux alentours du puits de production.

La création d'une porosité artificielle, en plus de la porosité naturelle, est requise dans d'autres domaines d'extraction d'énergie *stimulée*, par exemple pour certaines roches pétrolifères (tight gas reservoirs) et les schistes contenant du gaz (unconventional gas).

En fait, on distingue le cas de la roche chaude sèche, pour lequel le fluide se réchauffe dans sa migration horizontale au contact de la roche, et le cas de la roche chaude humide où des échanges de masse fluide entre la roche et le fluide ont lieu. La déformabilité de la roche doit être prise en compte, elle permet d'ouvrir les fissures dans la zone d'injection du fluide dont la température est bien sûr plus basse que celle de la roche. En fait, l'effet thermo-élastique non seulement ouvre les fissures dans la zone d'injection, mais les ferme à distance et limite donc les pertes de fluide injecté (leakoff). Il faut bien sûr modéliser la diffusion de l'eau, les échanges thermiques entre la roche et les fluides, et la convection de la chaleur. On a donc affaire à un problème couplé incluant mécanique, thermique et transport.

Aucune énergie dite alternative ne vient sans son lot de désagréments. Le mini-séisme du 6 Janvier 2007 occasionné par les essais de fracturation hydraulique qui ont été menés à Bâle en sont un bon exemple. Quoique d'une magnitude de 3.4 sur l'échelle de Richter, le mini-séisme a peut être reveillé les peurs ancestrales associées au séisme destructeur de 1356 de magnitude estimée 6.5. La ville de Bâle est bâtie sur les failles du fossé rhénan qui occasionnent une micro-séismicité continue. Le dilemne est que les sites géothermiques sont typiquement situés dans des zones sismiques, et pour de bonnes raisons. Le site de Bâle a été fermé.

Research topics

1. thermal recovery, fluid and heat flows in porous and fractured media;
   coupled effects of pressure and temperature on rock deformation;
2. permeability enhancement by hydrofracturing, by chemical agents;
3. computational aspects, heat convection;
4. sustainability of EGS: induced seismicity, leakoff and incidence of acidizing on environment.

Marine geotechnics: geohazards, stability of gassy sediments and marine slopes

Gas trapped in sediments covering the ocean floor may be biogenic, due to bacterial activity, or thermogenic, due to the transformation of buried organic matter under particular conditions of pressure and temperature. Gassy sediments are observed in deltas and continental margins all over the world while methane hydrates form in continental slopes.

Gas upward migration is thought to be continuous unless their progression is hindered by an impermeable fine-grained layer. This configuration is prone to catastrophic gas bursts, either naturally when the gas pressure is high enough to fracture the layer, or associated with seismic activities, or when triggered by anthropogenic aggressions. Gassy sediments represent geohazards for subsea installations since they are instable under loads. Gas continuous production results in heave while gas release produces subsidence. Both gas seeps, associated with faults, mud diapirs, and mud volcanoes, and gas bursts are potential threats for sea-bottom cables, pipelines and oil-related facilities.

Indeed, often, free gas is spread along thin horizontal or subhorizontal layers below an impermeable horizon, which may be punctured by the drilling activities. Alternatively, oil extraction decreases the pressure around the borehole, which therefore attracts gases, which may later continue their upward motion using natural pathways or through the exploration or exploitation devices. Once freed, gas may also move upward in the sediments either through diffusion or by hydraulic fracture if the pressure is larger than the fracturing pressure of the soil.

Gas upward migration may also use existing faults. Re-activation of the North-Anatolian fault during the next earthquake is feared to provide a way up for the gas trapped in the floor of the Marmara Sea just offshore the highly populated Istanbul area: indeed, according to observations by Ifremer, gas emissions are observed over the parts of the fault that have been active recently.

Even slight disturbances of existing natural gassy deposits may occasionally have severe consequences. As it has just been indicated, free gas naturally spreads over horizontal or subhorizontal zones, below an impermeable layer. The presence of gas can then be seen as creating an interfacial zone of weak resistance, with a very small shear strength. Catastrophic massive landslides are expected either when the gas pressure is sufficient to oppose the stabilizing effect of the weight of the top layer, or when the length of the weak zone becomes too large to be stabilized by the cohesive ligament provided by the top layer. The 1979 landslide of the Nice airport is suspected to be linked to such a mechanism.

Mechanical stability of gassy sediments needs to account for the nature of the soils, the presence of gas being known to affect the shear strength of clays but not of sands. The presence of gas leads to a dramatic decrease of the longitudinal wave speed, and to an increase of the electrical resistivity.

Upon gas burst, the depression created in the sediments attracts sea water. The consequences on the mechanical properties of the sediments of such a replacement are to be scrutinized.

Understanding the modes of upward migration of gases has further implications in regards to (1) stability of formations containing methane hydrates and (2) projects of carbon dioxide sequestration in marine sediments. Gas pressure, earth lateral stress, soil cohesion, interfacial tension and soil particle size are suspected to govern the modes of gas upward migration, namely by capillary invasion of the pores, or by fracture of the particulate network.

Research topics

1. stability of slopes sitting on weakened interfaces
2. sustainability of natural hydrate reservoirs and of carbon dioxide sequestration fields
3. modes of transport of gas in deformable multiphase mixtures

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Geomechanical issues for deep, ultra-deep waters and arctic regions

Deep water oil and gas production poses significant technical and management challenges to the oil industry, in line with huge investments, rental dayrates and expected paybacks.

Seabed sediments have often weak geotechnical properties. The shallowest meters are of special interest because the hydrodynamic forces induce dynamic interactions between infrastructures and soil. On-bottom pipelines to shore sink a small depth in the sediments and may be subject to large lateral motions due for example to thermally induced axial buckling. Conversely, they cross zones where currents may liquefy the sediments and result to be buried. Appropriate protection should be devised to counter, or minimize, the mobility of the sea floor sediments.

Remoulding of weak sediments due to these dynamic interactions is a key challenge for a geomechanical modeling approach. Undisturbed and remolded strengths have been reported in specific cases to vary by a factor 5 or more. Carbonate soils present additional challenges, being highly contractile, collapsible and liquefiable, while some strength can be mobilized at relatively large strains. Geophysical methods provide only elastic moduli, and have their own limitations in case of irregular vertical and/or horizontal heterogeneities. In any case, obtaining high quality samples from deep waters is a dounting task, and analyses may have to rely on a combination of laboratory tests and in situ measurements.

Systems floating over more than 2000 m water depth are stabilized through anchors, that oppose vertical uplift, in contrast to gravity platforms that are sustained by (essentially) compression foundations. The moorings should resist cyclic loads induced by waves, currents and wind. In the Artic Region, the motion of ice masses at breakup exert huge horizontal efforts on platforms. At great depth, taut moorings are preferred over catenary moorings. Taut moorings are realized by suctions caissons, or drag embedment anchors. The response of suction caissons under cyclic loading or with partial drainage requires further research. Embedment anchors resist a priori horizontal loads. However, taut moorings are associated with a vertical load, and the prediction of the behavior of anchors under such a load is a research topic. Besides, the issue of the most appropriate mooring for a given type of sediment has been only partially addressed.

Deep water offshore facilities are subject to a number of geohazards, like active faults, sea floor slope instabilities, seafloor erosion, shallow water flows and gas hydrates. Sea floor instabilities may be due to an evolving over-steepening associated with local uplift of salt formations, or tectonics. Shallow over-pressures lead to drilling difficulties and may be mitigated by casing above the overpressure zone. In the Gulf of Mexico, water pressures above hydrostastic level exist in unconsolidated sands at some depth below seafloor. The overlying soft clays may be easily fractured during drilling operations. The geological and geomechanical conditions that lead to the formation of overpressured zones are not well understood. While large zones of gas hydrates can be detected from seismic reflection through a characteristic reflector, sparse pockets are more difficult to locate. Local increase of the temperature due to drilling and production may contribute to partial melting and subsequently reduce the bearing capacity of the zone and endanger the structures.

Research topics

1. carbonate soils ; remoulding ; soil mobility
2. soil-structure dynamic interactions
3. mooring systems

Reservoir geomechanics : conventional and unconventional gas and oil deposits

Inclined and horizontal drillings, borehole stability

Inclined and horizontal drillings allow to restrict the rig zone but the wellbores are more prone to instabilities. Calibration of the supporting mud between the compression and extension failure limits becomes an issue. The anisotropic properties of the rock become crucial, and the analysis turns more tricky, given that the borehole is inclined with respect to the orthotropy axes of the formation. Assessing the failure of the borehole should consider elastic-plastic models, and test likely stability and bifurcation modes in a three-dimensional, or at minimum generalized plane strain, context.

Chemo-mechanical couplings triggered by the contrast in chemical content between the drilling fluids and the rock have become an integral part of the wellbore stability analysis in shale formations. Similarly, thermo-mechanical couplings may need to be accounted for as temperature is known to weaken the strength of rocks.

Determination of in situ stresses is of particular importance in tectonically active zones and salt diapirs where the principal stresses may be inclined to the vertical direction and higher than lithostatic.

Tigh gas reservoirs

As peak oil has or is being passed, reservoirs which were deemed too expensive to exploit in the past come back in the window due to the increased pricing of the resources and to technological advances. While conventional oil and gas flow unassisted out of the rock through vertical wells, unconventional gas is much more difficult and costly to extract. Unconventional gas includes shale gas, coalbed methane, gas at great depth and in geopressurized zones, gas hydrates found in permeafrost and ocean floor, and tight gas. Tight gas refers to gas locked in very low permeability reservoirs, less than 1 millidarcy, while conventional permeability is of the order of 0.1 darcy. They are found mostly onshore in sandstones, as well as in shales, coal seams and carbonates. Compaction over geological periods has induced cementation and/or re-crystallisation. Pores in which the gas is trapped are heterogeneously spaced and poorly connected.

The production needs to be stimulated. Enhanced recovery techniques aimed at improving the permeability of the rock rely on fracturing and acidizing. Acidizing consists in injecting acids to dissolve limestone and calcite cement so as to recreate a permeability network.

Both stimulation techniques require geomechanical expertise and development. Proppant embedment is an issue in tight gas sand reservoirs. Simulation of acidation, accounting for an increased viscosity of the reactive fluids, and their mechanical consequences at the grain, pore and macro-levels are open issues. Similarly, characterization of the fractured network (aperture, density, orientation) and its impact on the geomechanical properties of the undisturbed reservoir and after fracturation are key issues that govern the production rate. Dual porosity dual permeability models are candidate frameworks to embed the coupled mechanical and transport aspects. A comprehensive analysis should involve the geomechanical and geochemical aspects, including potential thermal effects, non Darcian flows, presence of highly saline brine, and sorption, during the drilling stage and the whole production period of the well.

Anisotropic properties of the rock and knowledge of the in situ stress state become critical issues for well placement and multi-stage hydrofracturing in horizontal veins.

Underground injection of fluids is an operation common to several energy and environmentallly related activities, e.g. in geothermal sites, for carbon dioxide sequestration, for waste water disposal, and of course hydraulic fracturing. The induced seismic risk should be estimated. Conversely, in absence of fluid injection after the well has been abandoned, thorough depletion may induce surface subsidence.

Onshore drilling activities of tight gas and other unconventional reservoirs recovers, together with gas, flowback fluids containing not only the injected chemicals but also some natural components, that have developed and have been sitting at depth over geological periods, and that can be toxic to the environment. Disposal of flowbacks in saline aquifers requires to consider the potential chemical reactions with the aquifer rocks, and the consequences in terms of mechanical stability and in terms of permeability.

Storage of solar energy at low temperature by ettringite

Energy storage by sensible heat that utilizes the heat capacity of the material has a capital disadvantage that it requires excellent, and therefore expensive, thermal insulation.

Ettringite is a cementitious material which has long been targeted as a candidate for seasonal solar storage device. Its energy density of storage is, at low temperature, the highest among a number of potential materials, and storage and recovery are reported to take place reversibly.

The energy exchange process uses cycles of dehydratation and rehydratation. Dehydratation, where hydroxy groups and water molecules are extracted from the material, is endothermic, with a large latent heat in the range of 500 kJ per kg. It takes place between 30 and 55°C, according to published data. Energy recovery by rehydratation may take place at any temperature. The released heat is captured by a heat exchanger.

The process is environmentally friendly. Still technological challenges regarding durability over a large number of dehydratation-rehydratation cycles are yet to be addressed.

Fuel cells : mechanical durability of the electrolytic membrane

Fuell cells transform chemical energy primarily to electrical energy, and secondary to thermal energy. The electricity delivered is thought to be used in a number of portable or fixed appliances (portable phones, computers etc.). In the automotive and aerospace industries, the electric engine is also expected, if not to replace, at least to work in cooperation with a heat engine, that relies on fossile fuels.

An electrochemical combustion of hydrogen (to be delivered) and oxygen (contained in air) produces electricity, water and heat. The catalyst-loaded electrodes, which are the places through which diffuse the electrons, are separated by an electrolytic membrane. This membrane allows for the diffusion of protons and water, but it should be impermeable to the reactant gases, since, otherwise, the cell would not be operational. The relatively severe cyclic changes of temperature and hydration, that accompany the electricity production, are likely to affect the mechanical stability of the membrane in the long range.

Current fuell cells utilize perfluorosulfonic acid membranes that are typically about 50 μm thick. The formation of cracks (pinholes) provides pathways to gas and therefore decreases proton conductivity. The presence of negative fixed charges, mostly like in certain geomaterials, e.g. active clays, or biological tissues, e.g. articular cartilages and the corneal stroma, gives rise to electro-chemo-mechanical couplings, namely swelling and shrinking, Thermal cycles associated with the normal operation conditions of the cell induces a strong variation of hydration, and shrinking is obviously bound to create tensile stresses, which are likely promoters of pinhole nucleation.

In addition to being sensitive to hydration, ionomers, like Nafion®, present the expected time-dependent mechanical behavior of polymers, namely relaxation and creep. Creep is known to be sensitive to both hydration and temperature, and it is observed to lead to excessive deformation and rupture when the polymer chains can no longer disentangle.

Research topics

1. Creep, fatigue and fracture of the Nafion® membrane ;
2. Electro-thermo-chemo-mechanical processes : influence on the life time of the membrane

This topic is not really geomechanics, but it is linked to the above geomechanical issues via the key influence of electro-chemo-mechanical couplings.