Soils for engineers

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The very diverse soils on our planet require the expertise of specialized engineers to carry out civil engineering projects, in conjunction with other specialists. This specialist highlights the soil properties to be taken into account and characterizes them with appropriate tests, so that the foundations of civil engineering structures are sufficiently stable, with a safety reserve. Particular attention is paid to design tools for modelling the soil-structure interaction during the life of a structure. The inspection of the surrounding site provides a permanent record of the condition and possible movements of the supporting soil of a building throughout its life. Today, at the cost of soil improvement and reinforcement work, very large structures can be built in areas that were once considered unsuitable for any particular location. Current construction methods, which are less and less disruptive in urban areas in particular, make it possible to push the limits of what is possible beyond what was once imaginable.

1. Why soils require attention

 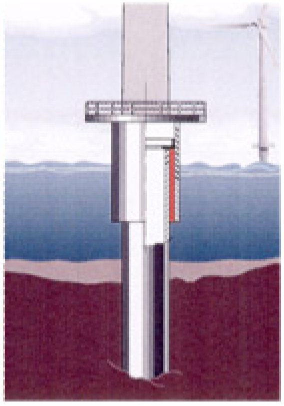

Figure 1. Offshore wind turbines 5 MW, seabed at 30 m, 110 m off water, 110 m emerged, on the left weight base of diameter 30 m, on hard rocky soils (granite); on the right foundation on driven and/or drilled monopile of diameter 6 m, on soft rocky soils (chalk). [Source: A. Puech, 2008, Marine Geotechnical Engineering Course, ENSHMG]

Let's talk about construction first: All **major land-based structures** (dams, bridges, viaducts, high-rise towers, silos, petroleum and chemical reservoirs, power generation plants,...) require foundations. As for **underground structures** (tunnels, galleries, underground factories, gas storage tanks,...) they must support the action (commonly known as pressure) of the ground. Finally, *offshore* structures, which are subject to marine elements, draw their stability from their support on the seabed (weight structures, figure 1) or from their anchorage on the seabed (floating structures, jackets, figure 2, or monopiles, figure 1, oil pipelines).

 

Figure 2. On the left, one of the jackets elements supporting an offshore platform, up to 300 m of water, size and weight comparable to those of the Eiffel Tower. On the right, jacket equipped with flotation ballasts towed on site; pile (diameter 2 m, length 50 to 100 m) guide sleeves for nailing on the sandy seabed. [Source: A. Puech, 2008, Cours de géotechnique marine, ENSHMG]

But soil is a "living" material, likely to evolve over time under the influence of various natural and anthropogenic phenomena, both planned and unexpected. We will therefore also have to deal with **soil reinforcement** in contact with the structure, and/or **remediation of** any disorders that may occur.

A specialized engineer (the geotechnical engineer and more often a team of geotechnicians) is in charge of the interaction between soil and structure (soil-structure interaction). He is of course in close contact with the team responsible for the work itself. In the rest of this text on soils, we will use the term engineer to refer to the geotechnical engineer.

When the idea of a major civil engineering structure, useful in principle, comes up, part of the preliminary project consists in closely examining the entire environment it will undergo and modify. We must therefore consult **the annals of local natural phenomena** likely to affect the deformations and stability of the construction over time (rain, snow, drought, flood, storm, freeze-thaw, earthquake, explosion,...). But a broad impact study (physical, hydraulic, ecological, socio-economic,...) is also essential to assess the repercussions of the structure on the nearby and distant site. The interests of individuals and the general interest are often in conflict. For example, the installation of the Aswan dams has completely changed the conditions of agriculture in Egypt: beneficial effects in the Upper Nile Valley (irrigation), but disastrous on the Lower Valley (salinization of land, lack of fertile annual alluvium).

So, if there is nothing fundamentally wrong with construction, we enter the project phase (the precise design of the structure and its interaction with the ground).

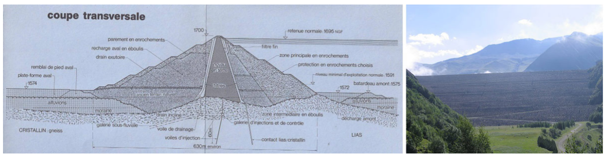

Figure 3. The Grand-Maison earth and rockfill dam on Eau d'Olle river in the Alps, commissioned in 1988. One of the world's largest dams, 140 m high, 550 m long at the top. Above section showing the core (clayey waterproofing), the waterproofing curtain in the river bed, completing the waterproofing, the rockfill refills, upstream and downstream, ensuring stability. On the right, photo of the dam and reservoir, seen from below. This dam is the upper part of a WWTP (pumped energy transfer station, 1820 MW, 300 Gwh/year), which allows the unused electrical energy to be stored in hydraulic form during off-peak hours. [Left, source: Comité français des barrages et réservoirs, 2012, Technologie des barrages] ; [Right, Douchet Quentin, source : GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons

Under the term soils, we mean soils and rocks, located under the vegetable and/or organic terrestrial layer. They are all natural materials, all different from each other, by their mineralogy, their granulometry, their possible cementation, and finally by the whole history of their formation. However, they are grouped into large classes with neighbouring properties, gravel, sand, silts, clays, more or less hard, more or less tectonized rocks. Water is almost always present, saturating the soil (under the roof of the water table), or accompanied by air (unsaturated soil) above the water table. In an earth dam (Figure 3) the materials are carefully selected according to the areas.

2. Important soil properties and their characterization

The essential tool of the soil engineer in charge of a civil engineering project is mechanics. Therefore, its most examined properties are its **mechanical and hydraulic properties**, namely its rigidity (modulus of elasticity), its strength (cohesion and friction), its dilating or contracting tendency to rupture, its permeability, and its reaction to hydration/dehydration. The anisotropy of these properties is always considered. The pore pressure in a soil leads the engineer to consider the total stresses and the effective stresses, the latter being those actually supported by the soil skeleton.

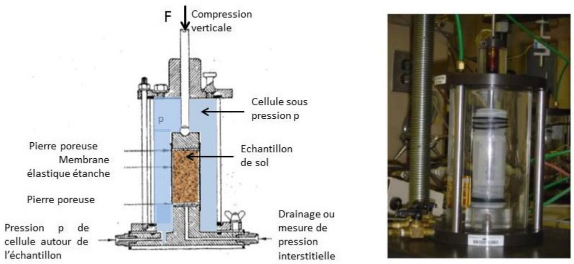

Figure 4. The triaxial test is used to characterize the rigidity and strength of a deep soil. On the left, the principle of the test (metrology not shown). On the right, picture of a triaxial cell. The cylindrical sample is subjected to a confinement stress p (simulating depth), then compressed (axial force F representing the action of a nearby structure), from small deformations to failure. [© Marc Boulon]

A preliminary project for a structure built on/on the ground requires the identification of the local soil. We are talking about **soil investigation**. The engineer will first obtain his first information from the geologists, complete it with the files - if they are accessible - of previous neighbouring constructions, and must finally order either boreholes / cores (for laboratory tests - triaxial, figure 4, direct shear, oedometer,... -, or in situ tests (penetrometer, pressuremeter, seismic refraction,...).

Laboratory tests directly provide hydro-mechanical data. On the other hand, *in situ* tests can only be interpreted by correlations with hydro-mechanical parameters, with a certain uncertainty. Soundings, penetrometer tests, pressuremeter tests provide local information (according to a vertical), while well-conducted seismic tests provide information about the ground in its mass, highlighting its heterogeneities. Many other techniques are available to characterize the subsoil layers: electrical conductivity, gravimetry, radar, which also help to detect cavities and discontinuities - faults, fractures -.

3. Design tools for soil

Classically, we talk about the structure in project (the bridge, the dam, the power plant,...), and the ground that must support it or even constitute it (earth dam, for example). During the life of the structure, **the soil-structure interaction is permanent**.

Equipped with the characteristics of the local soil (§ 2), the engineer evaluates the service and exceptional loads of the structure on the ground. Then the project is defined and the structure is completely dimensioned by ensuring one or more **safety factors**, obtained by estimating failure scenarios by increasing the loads or by reducing the soil characteristics. **National and international standards** (including Eurocodes, Eurocode 7 for soils) have been developed and gradually refined to assess safety, taking into account duly recorded and meditated historical disorders and accidents. But the actual deformations of the ground and the structure, before any failure, are also relevant in terms of the health of the structure.

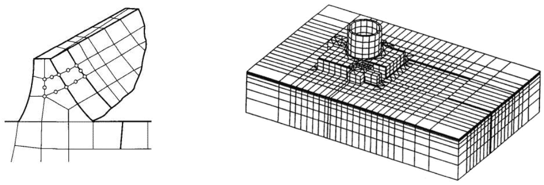

Figure 5. Meshing of 2 structures in finite elements. On the left, a dam (very simplified) and its valley. On the right is a power station and its nearby site. The method consists in writing the mutual equilibrium and deformations of a large number of small volume elements, each made of materials with their own rigidity and strength. [Source: MESTAT, P., (1997), Finite element meshes, advice and recommendations, BLPC 212, 39-64]

The engineer has **tools** at his disposal **to model** how works a structure and the surrounding site, using conventional or more advanced methods. It should be noted that these methods are constantly being improved, thanks to the dialogue between professionals and researchers. Traditional methods are mainly oriented towards safety. They assume the plastic rigid ground, i.e. not deforming before it breaks up suddenly. More recent numerical methods (in particular the finite element method, Figure 5) provide the soil with complete constitutive laws that reflect deformations up to rupture, and the rupture itself. They provide access to both the safety assessment and the deformations of the structure in service and the ground (typically a dam and its nearby valley). Today, classical and recent methods coexist in the profession.

We have just mentioned numerical modelling (finite elements) as a good predictive tool for the engineer. But the prediction can only be satisfactory if the hydro-mechanical data that feed it are representative. However, the initial characterisation of the soils (§ 4), at the time of the project, is always approximate, simply because of the heterogeneity of the subsoil. For example, miners digging a tunnel or a gallery tell you that they really only know the ground they are crossing when they excavate it, when they are driving it. This is where the power of finite element numerical modelling can be harnessed. The phasing of the work (the successive stages of construction) is simulated, the results of which are compared with on-site measurements during this work, from the beginning (the virgin site), of the modifications of the hydro-mechanical variables of the soil (displacements, stresses, interstitial pressures,...). This provides the basis for an inverse analysis, allowing the **soil project parameters to be corrected as the construction progresses**. This results in a more realistic definitive simulation of the structure's behaviour in service and under exceptional loading. This so-called observational methods also make it possible to rethink the initial project, in case it has been too bold, to the point of no longer meeting the safety criteria.

4. The auscultation of structures and soils

The measures accompanying the construction of the structure, on the ground and on the structure itself, have just been mentioned (§ 3). But a structure and its site have a very long life, after construction. For large structures, as well as for ongoing and identified risk situations (landslides, rockfalls,...), **programmed measurements of site hydro-mechanical variables are common**, constituting the auscultation. To be useful, this approach requires rapid interpretation and dissemination in real time. Thus, on a landslide, an acceleration of movements without modification of loads means a rapid evolution towards sudden rupture, and must trigger the alert of threatened populations. The structures (and their sites) commonly ausculted are dams (and the slopes of their valleys), power plants, bridges and viaducts (for which differential settlements are feared), tunnels and galleries (for which limited convergence is ensured, resulting from the movement of the faults crossed, or from the alteration of the surrounding rock. The devices installed are extensometers, inclinometers, settlement, pore pressure and groundwater level sensors, topographic survey tools,..

In the past (on the scale of the century(s)), the engineer had at his disposal rough measuring instruments (theodolite for displacements, level for inclinations,...). We are nowhere near these proven measurement technologies. New technologies have a prominent place in geotechnical engineering. Today, topographic movement measurements are carried out quickly, automatically and precisely using GPS. Extensometric and inclinometric measurements use optical fibre. In tunnels or galleries, all guidance and convergence measurements are based on laser techniques. UAVs and image analysis techniques are used to monitor the condition of large facings (dams, bridges, etc.). And many other new technologies are expected to be included in the panel of auscultation tools.

5. Soil improvement and reinforcement

Figure 6. A high retaining wall made of "reinforced earth wall". Each wall level consists of joined reinforced concrete "scales" anchored by friction in the upstream embankment by means of metal rods. The backfill is built as the wall is erected. This technique makes it possible to create aesthetic, stable, sub-vertical and draining walls. [Source: E. Lucas, P. Sery, A. Tigoulet, D. Brancaz, 2008, Les ouvrages récents de grande hauteur en sol renforcé, Compte rendus JNGG 2008, Nantes]

Soil can be reinforced preventively, or deformations, expected or not, can be corrected under or in the vicinity of a structure. There are many methods for preventive improvement. Let us quote the **compaction**, which is a hardening of the ground, practiced by rollers possibly vibrating, or by dynamic action (falling of heavy masses on the ground, explosions at ground level). In the case of very fine waterlogged soils, **drainage and consolidation** are chosen, by laying drains, or an electro-osmosis system, or by using atmospheric pressure by vacuum under a waterproof surface membrane. But the geotechnician must always be patient! **Reinforcement by geotextile sheets, micropiles, nailing**, is very common. In particular, nailing, using steel bars sealed in a borehole, passive or active (tensioning after sealing), is widely used to stabilize rock slopes and suspicious tunnel walls. Along roads and highways, armed embankments are often found (Figure 6).

Figure 7. The Rion-Antirion cable-stayed viaduct, made of reinforced concrete and steel, put into service in 2004, crosses the Strait of Patras in Greece, very seismic, by 65 m of water, whose seabed consists of a thick layer mainly clayey and soft. 2883 m long, based on 4 piers with a diameter of 90 m and a maximum span between piles of 560 m, it combines preventive measures. The clay under the piers is reinforced by a 30 m long forest of metal piles, which prevents a rotation of the soil-pier assembly. These piles are surmounted by a fusible granular layer (basalt blocks), allowing relative horizontal displacement (irreversible sliding) of piers during major earthquakes. On the left, view of the viaduct. On the right, the principle of improving the foundation soil. [Left, source: By David Monniaux (Own work)[GFDL (http://www.gnu.org/copyleft/fdl.html), CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/) or CC BY-SA 2.0 en (http://creativecommons.org/licenses/by-sa/2.0/fr/deed.en)], via Wikimedia Commons. [Right, © Marc Boulon]

Remediation of ground movements over time, programmed or not, is common. To correct differential settlement between bridge piers, the deck is periodically lifted. Cylinders have been placed between the foundations and the feet of the Eiffel Tower. In the centre of Mexico City, a clayey area very sensitive to earthquakes, large buildings are built on piles topped by cylinders in order to correct the slope of the building following each major earthquake. The Rion Antirion cable-stayed viaduct (Figure 7) is also designed to withstand earthquakes.

The most widely used technique worldwide to compensate for differential settlement is the injection of cement grout under foundation areas with excess settlement. But another original technique has recently developed. The worrying and increasing inclination of the Tower of Pisa and Mexico City Cathedral, built on a thick layer of clay, has been treated, in part, by under-excavation, or clay extraction under the highest foundation area. The recovery of these buildings was not intended, but rather the stabilization of their inclination (in addition to technical prudence, the tourist manna must be protected...).

6. Current trends and performance

Figure 8. Example of a tunnel boring machine. Tunnelling machines are of several types depending on the ground they cross, at earth pressure, sludge pressure, air pressure. The pressure is intended to stabilize the slaughter front. They are real rail-based factories, extremely powerful. The main parts are essentially, in order: the cutting wheel, the conveyor belt for the rear excavated material, a shield if the ground is soft, push reaction cylinders on the wheel, the cone shaped exhaust skirt, the lining segment erector (prefabricated), storage wagons. Outside a sludge treatment plant if sludge pressure. [© PHOTOPQR/LE PROGRES/PHILIPPON JOEL]

Trenchless works are preferred to earthworks whenever possible, as they generally do not harm the population. From small to large diameters, there are **directed boreholes**, which allow, for example, the installation of a non-rectilinear pipe (decimetre diameter) under a backfill, road, railroad, or even under a river if the soil is suitable. **Micro-tunnelers** offer an interesting perspective for drilling metric galleries. Finally, **tunnel boring machines** (Figure 8), of decametric size, are used to build tunnels even in very soft (sand, clay), saturated (case of the Channel Tunnel), very shallow (keystone less than 10 m from the ground surface) or very deep (Gotthard Tunnel in Switzerland, Lyon-Turin rail tunnel project with a maximum coverage of 2500 m of rock - and water !-). All these new tools are energy intensive!

Piles are the preferred foundation methods in soft ground, drilled or driven, commonly reaching several metres in diameter and a hundred metres in length in offshore. Cyclic loads are actively studied due to the so-called cyclic degradation phenomenon. To the extent that the capacity of the foundations is almost unlimited, provided that the price is paid, the structures themselves change in nature. For example, self-stable **cable-stayed bridges and viaducts** (Millau, Rion-Antirion,...) take precedence over suspension bridges

Today, on land, we are experimenting with **geothermal piles and structures**, with a dual function, foundation and heat exchanger.

Many other innovations are to come, which will mobilize the new generations..

References and notes

Cover image. The Grand'Maison dam by Douchet Quentin[GFDL or CC BY-SA 3.0], via Wikimedia Commons

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