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French national report on braced walls in soft ground

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SYNOPSIS: The following general report on french practice about braced walls in soft grounds describes the recent french experience about this kind of works applied to undergrounds projects, for "cut and cover" projects and for access shafts. It focuses about the different techniques currently used, either conventional ones or the new techniques such as soil nailing or jet-grouting, with their advantages and drawbacks, the structural design and ground movements assesment and monitoring. The existing codes of practice are also briefly reported.

1. PRESENTATION OF THE PAPER

The aim of this paper is to present the french practice about braced walls, mainly related to underground projects. Indeed braced walls may be used as a "cut and cover" alternative to true underground works when the depth and the environmental conditions make it possible, as it is generally less expensive that tunnelling, but also for the realization of the access shafts and metro stations.

It will decribe the main techniques used presently or in the recent years: both conventional techniques (classical braced walls, berlin walls, sheetpiling, diaphragm walls) and new techniques such as soil nailing and jet-grouting, which were intensively used or at least tested in the recent past years.

Afterwards we present a short decription of the current design methods for structural behaviour and deformation assesment, the monitoring of such structures, and finally a quick review of the existing codes of practice.

2. CONSTUCTION METHODS

The presence of a water table is one of the most important criteria for the choice of the construction method; various solutions are possible (cf fig. 1):

-if the soil is not too much permeable, it is possible to perform a water lowering, by checking that the flows are not too high and that there is no risk of piping;

-in soils with high permeability, it is generally prefered to perform an "impervious box": with watertight walls extended down to an impervious layer, or with a grouted bottom deep enough to resist to uplift water pressures, or with excavation and concreting below water. In these cases the retaining structure must withstand both earth and water pressures.

When there is no water table and some soil cohesion, the retaining structures do not require watertightness and may be discontinuous.

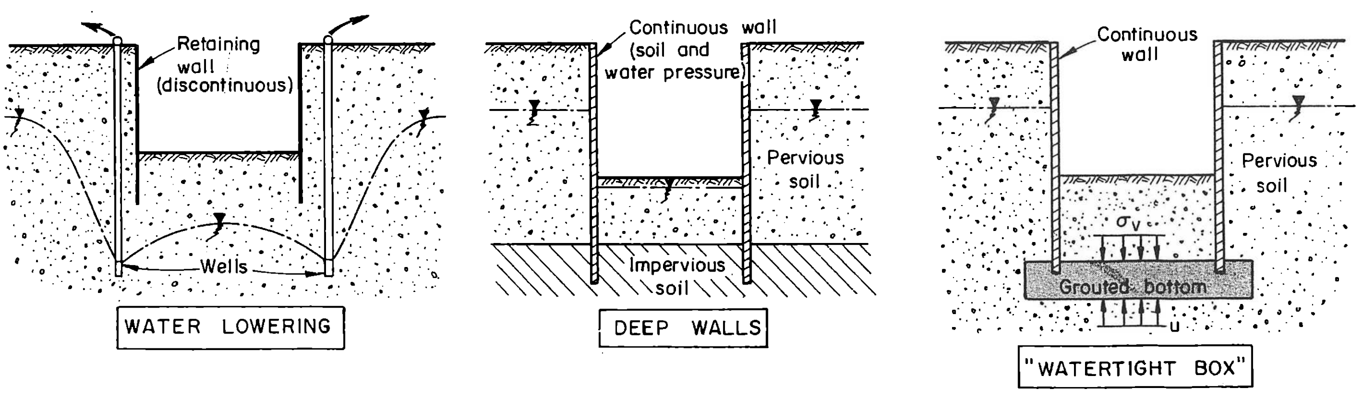


Fig 1. DIFFERENT KINDS OF RETAINING STRUCTURES BELOW WATER TABLE

2.1. Conventional methods

Classical braced walls, with excavation step by step, steel frames with timbering or shotcrete, and struts for retaining the earth pressures are widely used in grounds with some cohesion and whithout water table. They are often limited to small dimensions shafts.

"Berlin walls", with H shape soldier piles and timbering, are yet very often used. For small heights (up to 5 m) it may be designed as cantilever wall. For higher heights, they are associated with struts or grounds anchors, but may be restricted to non-sensitive areas or stiff soils, due to soil displacements risks behind the wall. Some alternative solutions to the classical method are used, with concrete piles or high inertia sheetpiles for the soldier piles, and shotcrete with mesh or cast-in situ concrete between the soldier piles.

Both previous techniques are generally restricted to projects above the water table and to soils with some cohesion. Otherwise they have to be associated with **soil treatment** as dewatering or grouting.

Sheetpiling, altough less frequent than twenty years ago, remains also a regular technique, associated with struts or tie-back anchors for deep projects, mainly in water-bearing ground. But their use is often restricted in urbanized areas for the environmental problems: effect of vibrations, driving difficulties in case of hard layers or boulders, presence of buried pipes or structures. Some risks for watertightness may also exist due to sheetpiles discontinuities.

Diaphragm walls, which appeared in France in the 60's, has now become a classical technique for many deep excavation (large civil works, underground car-parks, buried railways, metros or roads), as it combines the structural behaviour and the watertightness. The depth of panels already reached more than 100 m, while the excavation depth exceeded in some cases 50 m; their thickness ranges between 0.5 and 1.5 m. The panels excavation is done with cables or Kelly equipment, with a bentonite suspension for their stability; hards layers are excavated by trepaning, or by using the recent drilling equipment ("Hydrofraise" or equivalent).

Their large development is mainly due their numerous advantages in difficult urban areas: excavation very close to existing buildings, in hard beds, deepening down to more consistent substratum, integration to permanent structures. Watertightness is generally sufficient for provisional structures, and may be improved for permanent structures by special joints. Some difficulties appeared in few projects due to deviations of the panels, which caused sand bearing flows in the excavation: it reminds the fact that they require a high technicity from the specialized contractors.

"Prefabricated walls" appeared from the 70's based on the same principle as the diaphragm walls, with bentonite-cement suspension in the trenches (with a cement proportion which provide a strength at least equal to that of the surrounding ground). Then prefabricated panels are placed inside the trench, and are blocked by the cement strengthening (cf fig. 2).

The panels are excavated to the depth required for tightness, while the prefabricated elements are placed only to the depth required for ground retaining. As the concrete panels are prefabricated, with a better control of concreting, it allows thiner panels, together with a better aspect for permanent structures. These advantages may allow cheaper projects than classical diaphragm walls. Moreover some economical alternatives to concrete prefabricated panels may be used: sheetpiles, prefabricated slabs.

In some case, the use of a self-strengthening bentonite-cement grout (with a cement/water ratio of 0.1 to 0.4) associated with a steel mesh and vertical steel sections, proved to be satisfactory for small height retaining structures with no or small water pressures.

Curtains of secant or tangent piles are scarcely used in France, as the diaphragm wall is considered as safer and more efficeient. Nervertheless, for economical provisional structures in cohesive soils above the watertable, discontinuous curtains of reinforced concrete (or bentonite-cement grout) piles, with about one diameter spacing and shotcrete between the piles, proved to be efficient.

"Drop shaft sinking" is more and more frequently used for the execution of deep shafts (mainly circular and up to 10 m in diameter), even below the water table: it proved to allow a safe, quick and cheap method for the realization of shafts in poor soils, avoiding the costs of water lowering and grouting.

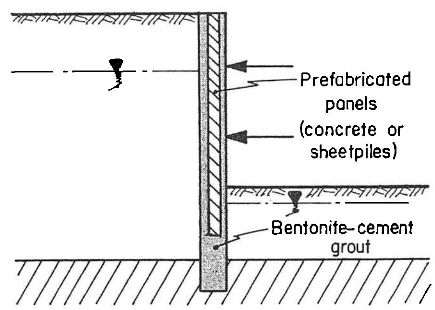


Fig 2. SCHEME OF A PREFABRICATED WALL

As already said, many of the previous techniques are associated -when their height exceeds 3 to 5 m- with struts or ground anchors. **Struts** are economical for narrow excavations (up to about 10 m); for larger length, the buckling risk leads to very large inertia sections, and ground anchors are generally prefered when possible (except in the angles where 45° struts are often used as substitution to the anchors). Struts are often placed without any prestressing, but monitoring revealed that their stiffness is often 5 to 100 times smaller than the one deduced from a simple compression behaviour (due to the self-weight deformations and connections defaults).

Ground anchors, either provisional or, permanent are widely used in France, with tensions of commonly 1 to 1.5 MN, above or below the water-table. Their small section and the use of high strength steel requires a prestressing in order to reduce the displacements of the walls. They are systematically checked by "normalized" procedures of tensioning and anchors tests, and protected against the corrosion when permanent.

2.2. New techniques

Among the new techniques which knew a large development in France in the past years, a special attention must be paid to **soil nailing**. This technique is performed by excavating step by step (generally 1.5 to 2 m high), and placing a shotcrete facing and nails (passive bars either driven or grouted in boreholes) with a regular mesh (1 nail for few square meters) at each excavation step. Sometimes, it is found more economical (or more safe with respect to soils displacements) to substitute passive nails by pre-stressed ground anchors.

This technique developped as it is generally more economical than conventional berlin walls or diaphragm walls. Nevertheless their range of application shows some limitations:

-the bars being progressively tensioned during the excavation steps, horizontal and vertical deformations do occur, which range between H/1000 and 3H/1000 (for a wall height H); this may be not acceptable in sensitive areas;

-during the provisionnal phases of excavation, a minimal cohesion is required to ensure the stability of the cut face: therefore it is unaplicable in granular soils under water-table.

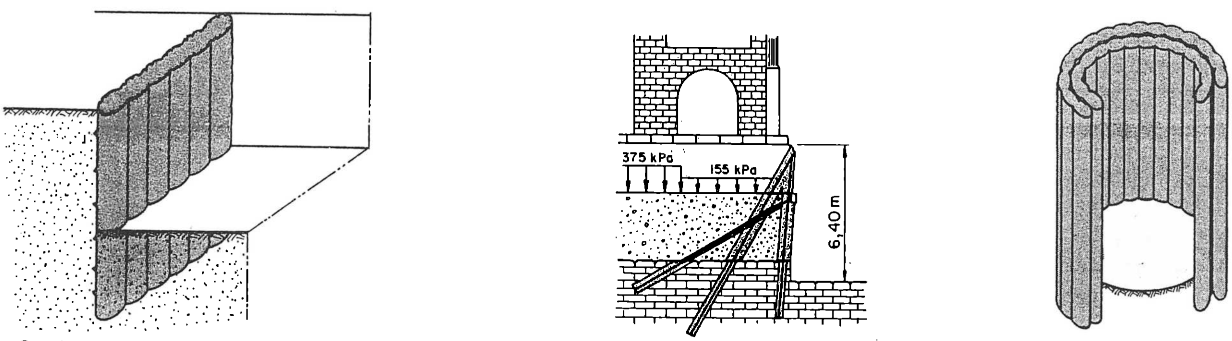
Jet-grouting found also some application to retaining structures (cf fig. 3):

-experiences with one line of vertical columns were not always satisfactory due to their small bending stiffness, when no steel reinforcing element is placed inside the column;

-a project for the "Louvre palace", just in vertical alignment with the historical facades, with three rows of columns (vertical, inclined, and sub-horizontal) proved to be very efficient to limit the deformations within a very small range (few millimeters);

-one or two secant rows of jet-grouting columns for circular shafts may also be attractive.

Nevertheless a very carefull attention must be paid for projects of deep columns in water bearing sands, where the unavoidable deviations of the borings (up to 1 or 2 %), or the discontinuities of the columns (mainly at the interfaces between hards and soft layers) may cause "windows" in the curtain and create sand-bearing flows during the excavation. As for the diaphragm walls, this technique must be performed by highly specialized contractors.



Single row of vertical columns — Complex structure. "Louvre" Palace — Double row of vertical columns (for circular shafts)

- *Fig 3. DIFFERENT SOLUTIONS WITH JET-GROUTING*

3. DESIGN METHODS

3.1. Evaluation of active and passive earth pressures.

Except for the FEM, all the existing methods requires the knowledge of limit values of the horizontal stresses acting on the structure. Active pressure is often calculated according to the Rankine theory, and the surcharge effect according to semi-empirical relationships, or derived from the linear elastic theory.

The passive pressure is calculated from the Caquot-Kérisel tables, by assuming a soil-structure friction angle ranging between $-\phi/2$ and $-2\phi/3$. A safety factor equal to 2 is generally considered when it is necessary for the wall stability (cantilever walls or with one row of struts or anchors). The seepage forces, due to the flows around the structure are to be considered, mainly for the uplift forces on the passive side, which reduces drastically the effective passive pressure.

The large effect of the cohesion on the active and passive pressure must urge the engineers to get a safe evaluation of this parameter.

3.2. Classical design methods

The traditional method of limit equilibrium is sometimes yet used for structures with only one level of strut, but it cannot be applied for pre-stressed anchors and for displacements estimation. For the conventional multiple braced walls, the Peck empirical diagram is sometimes used to calculate the efforts in the frames.

3.3. Reaction modulus design method

This method is very widely used in France for all the structures with multiple struts or pre-stressed anchors. The most commun computer program is RIDO, but several others have been devoloped by the highway laboratory (LCPC) and the specialized contractors.

It takes into consideration the soil pressures behind and in front of the structure (modelized by beams with bending stiffness), the water pressures, the effect of struts and anchors, and all the excavation sequences, step by step. The soil pressure varies with the wall displacements, with a generally linear relationship -modulus k_h- (but sometimes bilinear or hyperbolic), and cannot exceed the active and passive pressure, with an irreversible behaviour when a limit state has been reached.

The main difficulty is the accurate evaluation of the modulus k_h, which is not an intrinsic parameter of the soils, and cannot be directly measured. It is often deduced from empirical rules, or from the pressuremeter modulus E_M with consideration of the excavation geometry (BALAY - 1984). This widely used last method appeared in some cases to be pessimistic when compared to monitored values of deformations.

It must be pointed out that the movement assesment is always very difficult, when no calibration on similar soils is available, due to the hazardous prediction of soil cohesion and subgrade modulus. Moreover actual structures and reduced scale walls showed that the mobilization of the compression in passive struts is often under-estimated, probably due to the arching effect which is not modelized in this method.

3.4. FEM design

The FEM, although attractive as it may reproduce the arching effect, is generally used only for research works. Indeed it is consiered, up to now, too long and expensive for a regular use by the design firms and contractors. But a future development will probably appear soon.

3.5. Overall stability

An overall stability calculation has to be performed in order to check if the anchors length is sufficient to ensure the general stability of the structure, when not deepened down to hard bedrock. The TA 86 recommandations propose an alternative to the usual Kranz method, where the straight failure lines are replaced by a circular one.

4. GROUND MOVEMENTS ASSESMENT AND MONITORING

Monitoring of the structures and of the surrounding ground is very often performed for deep excavations and in sensitive areas, mainly in poor soils. In these case it is of main concern to check that the deformations and the mobilized efforts in the walls, struts and anchors have been accurately evaluated. Water table monitoring is also performed for projects with water-lowering, in order to check that the stability of the bottom is secured. Settlements measurements at ground level are less usual, as the main criteria is considered to be the horizontal displacement of the wall.

The commonly used monitoring methods are: topographic survey for the wall displacements, inclinometers inside the wall and in the ground, extensometry for the wall bending measurements, load cells for the struts and anchors.

It must be noted that such monitored structures are very interesting, for projects in somewhat homogeneous soil layers, in order to calibrate the calculation methods and parameters to be used mainly for assesment of the reaction modulus k_h and of the soil cohesion. Figure 4 shows the results of such a back-analysis for a section of the Lyon metro, which was used as a reference for all the subsequent calculations.

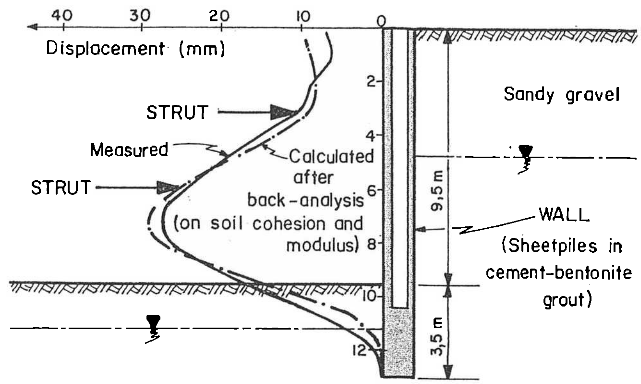


Fig 4. COMPARISON BETWEEN CALCULATED AND MEASURED DISPLACEMENT (after calibration of soil parameters) From KASTNER (1992)

5. CODES OF PRACTICE

Numerous publications about the design and behaviour of the different kinds of braced walls (geotechnical books, congress proceedings ...) exist, but very few official codes of practice.

It must be mentioned that the general rules of geotechnical calculations include more and more the "limit state principles", with partial weighting coefficients on the actions, and partial safety factors on the strength, but are not yet "officialized" for the retaining structures (except for soil nailing). They are indeed included in the project of "EUROCODE 7 - Part 1: geotechnical design, general rules", presently under preparation by the European Committee for Standardization, together with some very general rules about design of retaining structures.

Two existing recommandations for the design, calculation, execution and control of some retaining structures exist:

-for soil nailing: "Recommandations CLOUTERRE 1991";

-for ground anchors: "Recommandations TA 86".

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