Construction of Concrete Diaphragms (Cut-off Walls) in Italy

Construction de murs diaphragmes en Italie

by Edison Group (Milano),
S.A.D.E. Group (Venezia),
and
S.I.M.A. Company (Verona)

Summary

The authors describe concrete diaphragm walls built in Northern Italy by the Edison Group, Sade Group and S.I.M.A. Company during the past decade; they outline the development of the characteristics of these structures and study the various uses for which they were built, classifying them as: watertight diaphragm used for construction works, and diaphragm for many other applications. They consider each case on its merits, giving reasons for the choice of method, type of construction, properties of materials, scale model tests, and experiments undertaken to check both static and hydraulic stability.

Sommaire

Les auteurs exposent une brève analyse d'une série de murs diaphragmes construits dans le Nord de l'Italie par le Groupe Edison, le Groupe Sade et la Société S.I.M.A. dans la décade écoulée. Après avoir montré l'évolution des caractéristiques de ces ouvrages d'après les applications décrites, ils exposent les buts multiples pour lesquels ils ont été réalisés. Ils sont étudiés d'après leur destination en les distinguant en murs étanches, murs ayant une fonction dans la construction et en murs ayant des fonctions différentes. Toujours sur la base des exemples cités ils exposent ensuite de brèves considérations sur leur choix, l'exécution, les caractéristiques des matériaux, les études sur modèle, la vérification de leur stabilité et de leur comportement du point de vue statique ou étanchéité.

Introduction

The authors give a brief outline of several concrete diaphragm walls constructed in Northern Italy by the Edison Group, S.A.D.E. Group and S.I.M.A. Co. These were built during the past ten years, and they illustrate fairly well the development of this technique in Italy.

The structures considered are shown in the annexed table, which gives also their main characteristics (Tab. 1 and Fig. 1).

They are all concrete structures, poured in loose material, often reinforced, being about 50 cm thick. Excavation for their construction is generally kept open by means of drilling mud (bentonitic clay).

In the successive applications of these structures, the first examples are of diaphragms consisting of tangential piles, bored without using drilling mud: the diaphragm is thus formed by a succession of adjacent but separate elements, and therefore it is comparatively less efficient, particularly with regard to watertightness (Fig. 2).

A decisive improvement is represented by the diaphragm of interlocking elements obtained by partially clamping each element with an adjacent one and using drilling mud. By this method, however, it is not possible to obtain a cut-off wall of constant thickness, because the surfaces are formed by cylindrical segments, and the thickness of the diaphragm at the joints between elements is considerably reduced. To prevent this, a new technique was developed, introducing diaphragms formed either by elongated elements joined together or by a series of overlapping elements of smaller size (Fig. 2).

The diaphragms considered are generally multi-purpose, their main purpose being the modification of the conditions of filtration in the area involved, until complete watertightness is achieved.

Generally this main purpose is accompanied by several other specific aims according tow hich the diaphragms may be considered either as simple construction aids or as structures serving permanent purposes.

The former group includes diaphragms built to permit open excavation for foundations; the latter, diaphragms built as protective walls against erosion or as foundations.

(a) Watertight diaphragms

A noteworthy watertight diaphragm is that for the weir on the river Stura di Demonte near Pietroporzio, consisting partly of elongated elements and partly of tangential piles. It runs below the upstream cut-off wall of the left sluice of the weir and extends below the wing wall, crossing coarse alluvial soil in which there are numerous boulders exceeding one cubic metre in volume, their lower parts embedded in rock.

Two further examples of watertight diaphragms are those at Caprizi and at Maria at Lago, which are of interlocking element type.

The Caprizi diaphragm (Fig. 3), built below the weir in the bed of river Tagliamento, crosses an embankment of alluvial material and is sunk into calcareous silt without abutting on the rock.

The diaphragm below the upstream toe of Maria al Lago dam, Pian di Fedaia (Fig. 4) is poured in an embankment of alluvial and detritic material, with large boulders. One-half of the rocky bottom, to which the diaphragm is keyed, consists of limestone; the remainder is of tuff, which partly lies above the limestone. This diaphragm reached the maximum depth attained by this group of structures, viz. 41·90 m.

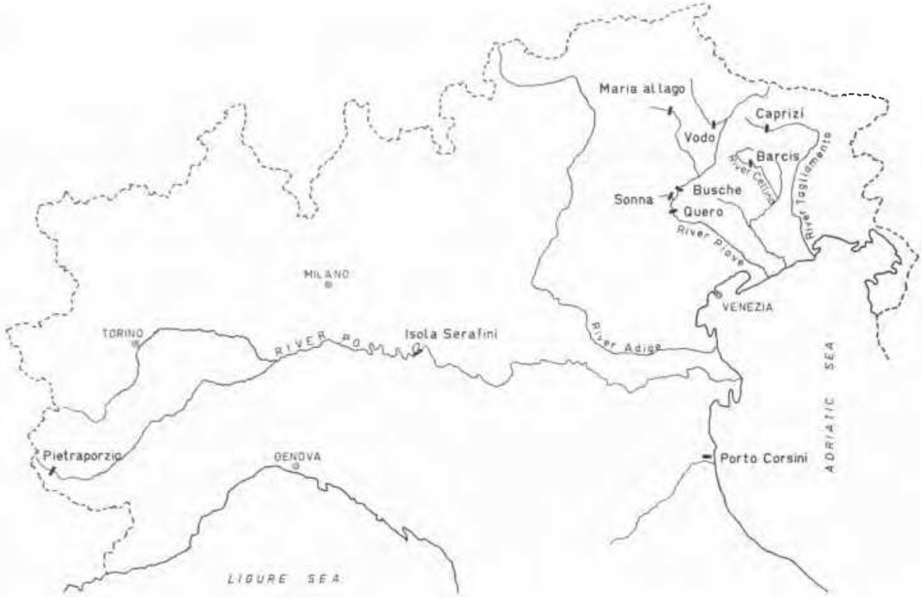

Fig. 1 Map of North Italy with location of diaphragms.
Carte de l'Italie du Nord avec emplacement des murs diaphragmes.

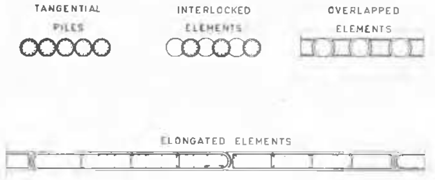

Fig. 2 Various types of diaphragms adopted.
Différents types de murs diaphragmes adoptés.

Another example is the diaphragm built at the Isola Serafini hydro electric power plant, on the river Po. This plant is particularly interesting for the large development (more than 66 000 sq. m) of diaphragms therein realized and the various functions for which they were built (Fig. 5).

The diaphragm in question, of elongated element type, is poured along the extension of the dam axis through the flood plain at the left bank of the river bed as far as the existing levee. The flood plain consists mainly of fine-grained material; the diaphragm has a length of 1 390 m and a maximum depth of 20 m.

The diaphragms of the Vodo dam are carried out into detritic alluvial and moraine deposists which form, on both sides, the upper part of the dam site. The diaphragms start from the dam abutments and cross in different way and length the loose material, both diaphragms consisting of overlapping elements.

The double diaphragm built in the bed of river Sonna, between the apron of the dam and the rocky bottom, is of the same overlapping element type. Both diaphragms were poured in coarse gravel containing large boulders which, in some areas, are very close together. In addition to providing watertightness they were used as a construction aid for the intake to the Quero power station downstream of the dam.

(b) Diaphragms as construction means

The tangential piles diaphragm built in the Cellina river bed (1951-52), was intended for the excavation of the turbine draft tubes for the Barcis power station, as well as restoring the bottom outlet of the adjacent dam. It thus formed a reinforced concrete arched diaphragm founded on an alluvial stratum grouted with silicate and cement.

The diaphragms built in the bed of the Piave, near Busche, for the Quero power station, has facilitated the excavation and construction of the intake wear in two stages, successively diverting the river, at first to the left and then to the right side. The first part of the diaphragm is 280 m long, the remainder 330 m.

Two methods of construction were followed : the elongated element system for soil consisting of fine material and for a depth not exceeding 8·50 m ; the interlocked element system for coarse soil and for a depth exceeding 8·50 m.

At Quero power station, the overlapped element diaphragm permitted open excavation of the foundation to be done in dry conditions, while another similar diaphragm facilitated the excavation of a section of the tail race, between draft tubes and tailrace channel.

Fig. 3 Diaphragm at Caprizi intake.
Mur diaphragme à la prise Caprizi.

The former of elliptical shape, has a length of 138 m (Fig. 6); the latter is smaller. Both cross the alluvial soil and are keyed into the rocky bottom, which comprises red scaglia on which the power station is founded; the water table head is about 17 m.

Diaphragms as construction aids were also employed at the Isola Serafini power station (Figs. 7 and 8). The elongated element type diaphragm forms a trapezium in plan with a perimeter of about 530 m and crosses mainly sandy material for a depth of 33 m thus penetrating for about 1 m into an underlying clay stratum. Open excavation was carried out within the diaphragm with conventional mechanical equipment, down to a depth such as to maintain a sufficient weight of material above the clay embankment to counterbalance the artesian pressure below it. Below this level, excavation was carried out with the aid of pneumatic caissons.

The upstream diaphragm was placed below the foot of the intake trash rack and as it had to be uncovered for the construction of the structure supporting the rack, it was backed by a series of reinforced concrete abutments carried out in the same way as the diaphragm around the perimeter. The abutments are spaced at 4·25 m centres; they are 11 m in length and 29 m in height (Fig. 9).

Elongated element diaphragms were also used at the new thermal power station of Porto Corsini, in order to facilitate excavation for the intake structures, down to a depth of 6·50 m. The diaphragm forms the vertical walls of the intake structure. The soil crossed consists of a layer of silty sand located above soft and sandy clay.

(c) Diaphragms serving various purposes

Among the diaphragms serving various purposes, the watertight diaphragm of Pietraporzio, mentioned above, has been used, together with a row of bored piles, providing support for a wing wall foundation.

At the power station of Isola Serafini, a large diaphragm runs through the flood plain at the left side, and is intended to prevent the formation of side beds in addition to providing watertightness. Other consolidation diaphragms were built along river Po levees to protect its banks (Fig. 5). The power station tailrace embankments are also protected by a diaphragm supporting the earth pressure, as well as the hydrostatic pressure initiated by a sudden lowering of the water level in the tailrace; this diaphragm is anchored by tie rods to another one behind it.

Among the diaphragms built at Porto Corsini (Fig. 10) power station, those below the fuel tanks and the generating units were carried out for the purpose of consolidation: in the former case they prevent displacement of the ground, thus decreasing the reservoir settlements; in the latter case, they withstand the horizontal pressure due to the superstructure and contribute towards a reduction of vibration and possible resonance between the units.

(d) Performance and behaviour of the diaphragms considered

On the basis of their experience, the authors give details of the design and performance of these structures, referring to the results achieved by their use.

The nature of the soil has determined the selection of excavation equipment, the composition and density of the mud to be employed and has influenced the stresses and wear imposed on excavation equipment, and its output.

No difficulty has been encountered with any diaphragm in loose material, where the maximum size of elements is 10÷15 cm.

In the case of a stratum containing large boulders at Pietraporzio a high percentage of excavation was due to the crushing of these boulders, so that it was necessary to use heavy equipment subject to considerable wear; there was also high consumption of drilling mud and difficulties were encountered in supporting excavation with this mud. This was partly due to the rudimentary state of this technique. In a similar case, at Busche, the pile type of diaphragm has been adopted — as already mentioned — for greater depths, although the rate of carrying out the work was slower.

As regards the sizes adopted for each element, it has already been pointed out that the thickness is generally about 50 cm. The width, in the elongated element type, has

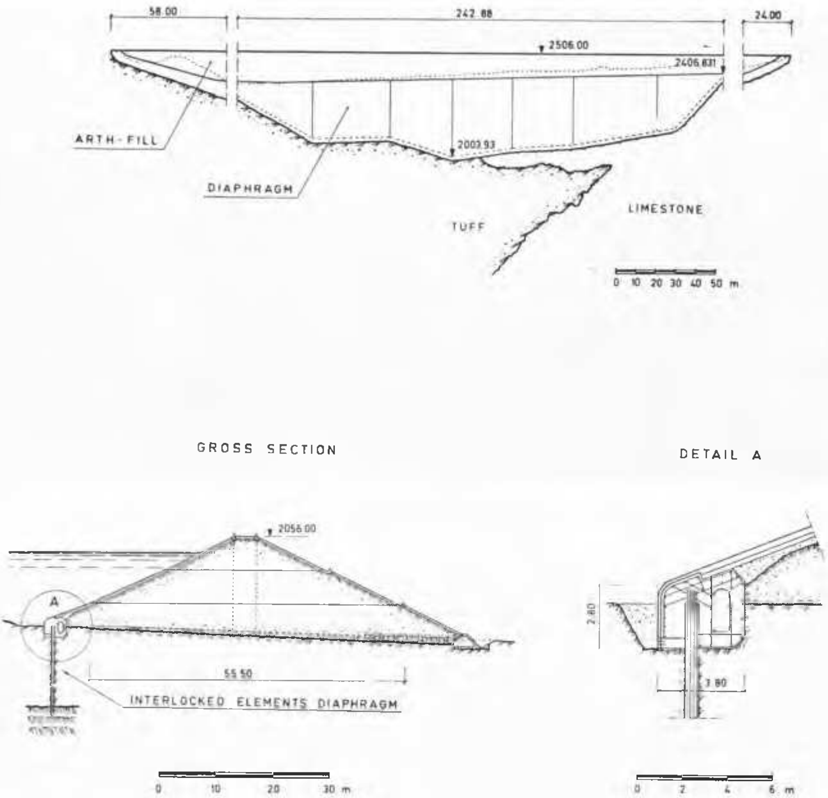

Fig. 4 Maria al Lago dam. Diaphragm.
Barrage Maria al Lago. Mur diaphragme.

generally been fixed, at from 4 to 6 m; however, sometimes 9 m were reached. In the overlapped element type the width of the element is about 1 m.

As seen above, the diaphragms here described reached a maximum depth of 42 m at Maria al Lago.

The lowest unit cost is achieved at a depth of about 20 m. For greater depths, difficulties may arise from the longer period for which the excavation remains open and from the performance of the joint between the various elements.

As regards performance, the critical period is generally the excavation stage, when drilling mud is used as a supporting medium. An accurate check of its preparation, adapting the density to the nature of the ground, will limit the danger of sliding. The addition of wood chips or cellophane strips, as practised at Pietraporzio, Maria al Lago and Isola Serafini, will hold up a sudden escape of mud, while the localized addition of cement-bentonite may be a suitable method of crossing an underground water table.

The cement batching usually adopted seldom goes below 250 kg per cub. m; for reinforced diaphragms the batching is 300 kg per cub. m. At Barcis, Pietraporzio, Busche, Quero, Vodo and Sonna, normal Portland cement type 500 was used; at Caprizi, Maria al Lago and for the various diaphragms of Porto Corsini and Isola Serafini, ferric pozzolanic cement was used, due generally to the presence of aggressive water.

The concrete used is of the chuted type: maximum size of aggregate 30 ÷ 40 mm. The high water/cement ratio is not conducive to high strength.

Sampling at Isola Serafini on the whole height of reinforced concrete diaphragms, 33 m high, gave a core percentage in excess of 90 per cent, showing a satisfactory compaction in the concrete-particularly in the lower part and the almost entire absence of voids.

Ductile iron was generally used for reinforced concrete, its maximum diameter being 32 mm. At Isola Serafini, Sonna and Quero round bars of hard steel with increased bond were also used. It seems that reinforcing steel does not decrease its bond with the concrete due the presence of a mud membrane, if any, on the surface. Careful tests were carried out to establish this at the Polytechnic School of Milan.

When particular static functions were required from the diaphragms, curvilinear shapes were adopted, as at Barcis and Caprizi, as well as elliptical or circular shapes suitably braced, as at Quero, or wing bracing by means of abutments

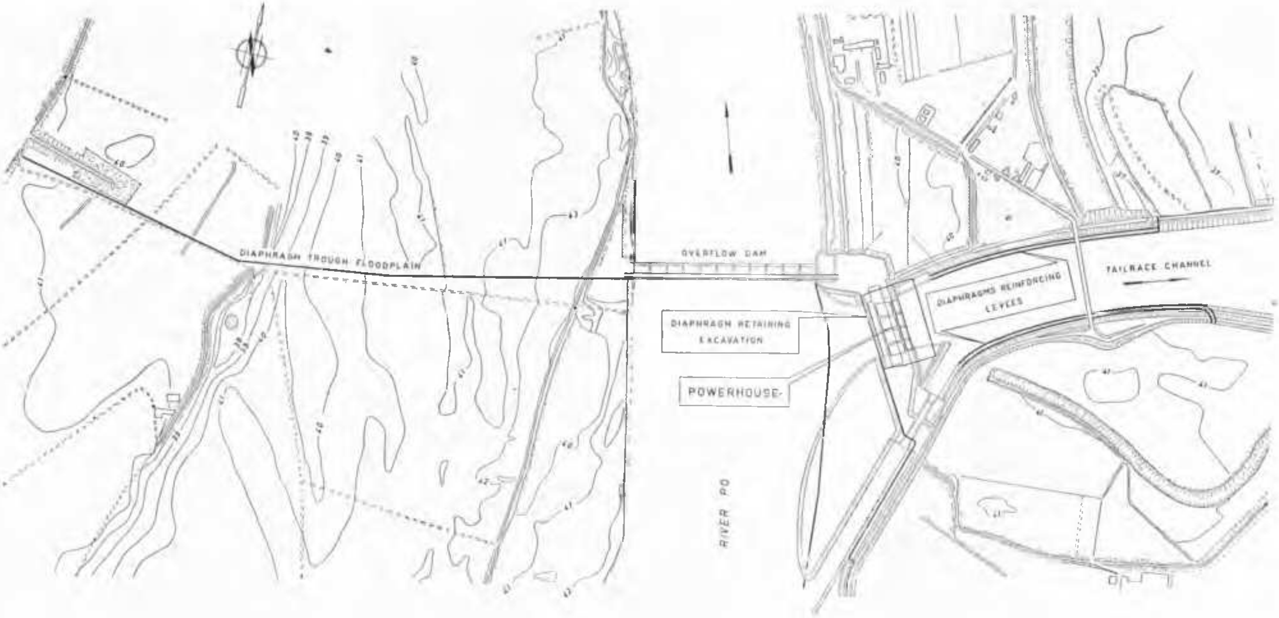

Fig. 5 Isola Serafini power station. General layout.
Aménagement d'Isola Serafini. Plan général.

Fig. 6 Quero power station. Elliptical diaphragm.
Usine de Quero. Mur diaphragme elliptique.

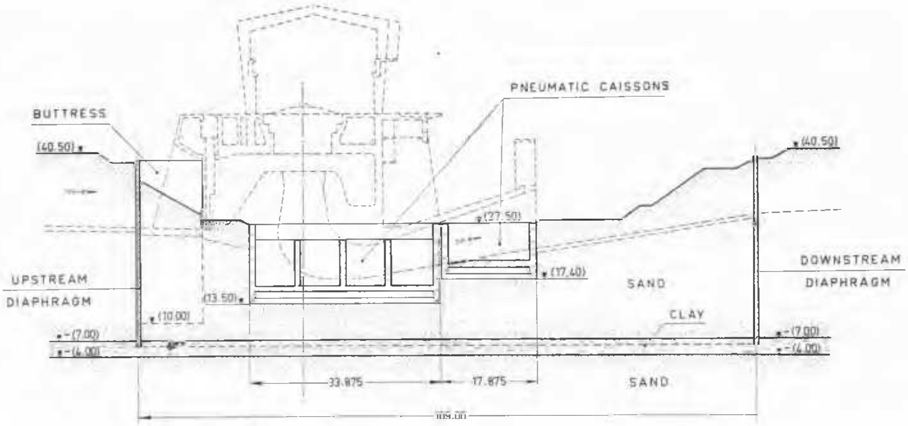

Fig. 7 Isola Serafini power station. Section through excavation.
Usine d'Isola Serafini. Coupe des fouilles.

built with elements of the same diaphragm as at Isola Serafini power house, or finally a double system of suitably spaced parallel diaphragms joined together in the upper part by steel or reinforced concrete tie rods, as also performed at Isola Serafini.

The diaphragm-abutment system at Isola Serafini revealed the presence of voids at the contact area between the two structures, as the construction of the abutments was considerably delayed with respect to the diaphragms. It would be better, in similar cases, either to pour new structures on green concrete, as practised for a normal joint between elongated elements, or to build T-shaped structures in order to prevent joints at right angles.

Static analyses were carried out based on the assumption that the forces operating were the active and passive earth pressure and hydrostatic pressure under various conditions, considering the structure as formed by vertical elements, either bonded at the base and supported at the top or simply bonded at the base. In the case of the Quero elliptical section diaphragm, where inner stiffening rings were added, these were calculated as horizontal arched strips, applying the elastic arch calculation.

An interesting model test was carried out for Isola Serafini : the filtration flows, which occur at the banks of the power station tailrace as a result of sudden variations in water level, were carefully studied on a sand model (Fig. 9).

In the case of retaining and support diaphragms, static analyses were extended to the whole earth mass involved (Porto Corsini, Isola Serafini).

An interesting preliminary deformation test for an interlocked elements diaphragm was performed on site at Maria al Lago. A sub elliptical section diaphragm, 35 m deep, was poured; from its internal part the alluvial material was then removed. A closing cover was built over the resulting well and water under pressure was admitted, so that wall were subjected to maximum stresses which would occur with the reservoir at maximum water level and without a downstream water table. The extensometers placed inside the

Fig. 8 Isola Serafini power station. View of excavations and abutment diaphragm.

Usine d'Isola Serafini. Vue des fouilles et mur diaphragme de culée.

Fig. 9 Isola Serafini power station. Power station diaphragm. Supporting abutments.

Aménagement d'Isola Serafini. Mur diaphragme de l'usine. Culées de support.

well showed a satisfactory elastic behaviour of diaphragm-ground system, both when under pressure or unloaded.

During construction and later during operation, static and hydraulic checks were carried out. At Isola Serafini the diaphragms retaining the power station excavations revealed movements in the form of horizontal settlements (some tens of centimetres in the middle areas), without showing any localized discountinuities. Such movements mainly occured during sinking of pneumatic caissons.

At Porto Corsini the foundations of the units were subjected to systematic checks of settlement with the aid of precise optical instruments; these settlements were uniform over a period of two years, their maximum value being 4 mm with a weight of about 5 000 tons over an area of about 230 sq. m. Careful loading tests were done on the foundations of the fuel tanks before the operation of filling with sea water was started : during filling, settlements were ckecked by means of precise levelling. In order to check ground displacements outside the diaphragm, external points were also levelled, no movement being, however, noticed. A check of settlements — the development of which is quite normal — is periodically carried out.

At Vodo, checks of diaphragm crest are provided by means of a triangulation net. Two months from the time that the reservoir was filled no appreciable movement has been noticed.

The behaviour of all the diaphragms has been satisfactory also in respect of watertightness.

At Maria al Lago, with the reservoir at top water level, losses through the dam (diaphragm + abutments) are about 150 l/sec (over a diaphragm area of 7 494 sq. m). From numerous investigations made, most of these losses are probably due to fissures in the lower part of the rock, not completely filled by grouting. At Busche, losses amount to a little more than 10 litres (over 4 337 sq. m); a few litres at Quero and Caprizi; in other structures no losses were noticed.

Table 1

Edison Group, Sade Group and Sima Co. Some concrete diaphragms constructed during the past decade in Northern Italy

Name of the structure	*Construction period*	*Type of diaphragm*	*Material crossed*	*Function of the diaphragm*	*Main sizes*			
					depth max. m	*depth mean* m	*length* m	*area* m²
1. Barcis	1951-1952	Tangential piles	Sand, gravel, boulders	Diversion cofferdam	10	9	25	225
2· Pietraporzio	1954-1955	Tangential piles	Gravel, boulders	Tightness and foundation	18	18	26	470
		Elongated elements	Gravel, boulders	Tightness	18	9·5	25	232
3. Caprizi	1954-1955	Interlocked elements	Sand, gravel	Tightness	16	14·3	75	1 077
4. Maria al lago	1954-1955	Interlocked elements	Sand, gravel, boulders, silt	Tightness	41·9	30·8	242·90	7 494
5. Busche	1957-1959	Interlocked elements	Sand, gravel	Tightness and excavation support	22·2	7·1	607·6	4 337
		Elongated elements	Sand, gravel	Excavation support	8·50			
6. Quero	1958	Overlapped elements	Sand, gravel	Tightness and excavation support	18·8	16·3	138·3	2 255
		Overlapped elements	Sand, gravel	Tightness and excavation support	17·5	14·7	79·2	1·168
7. Porto Corsini								
units	1958	Elongated elements	Silty sand, soft clay	Foundation retaining	12·5	12·5	80	1 000 × 2
tanks		Elongated elements	Silty sand, soft clay	Foundation retaining	6	6	120	720 × 4
intake		Elongated elements	Silty sand, soft clay	Foundation retaining and excavation support	6·5	10·6	70	800
dock	Being design.	Elongated elements	Silty sand, soft clay	Earth retaining	12·3	12·3	680	8 400
8. Isola Serafini								
powerhouse	1958-1959	Elongated elements	Sand	Tightness and excavation support	33	31	888	27 690
levees		Elongated elements	Sand	Bank consolidation	20	12	1 880	22 970
dam		Elongated elements	Sand	Tightness and protection against erosions	20	11	1 390	15 500
9. Vobo	1959	Overlapped elements	Gravel, boulders	Tightness	34·5	25·5	82·5	2 100
right		Overlapped elements	Gravel, boulders	Tightness	21	12·5	74·10	932
left		Overlapped elements	Gravel, boulders	Tightness and excavation support	25	13·3	82·1	1 096·2
10. Sonna	1959-1960	Overlapped elements	Gravel, boulders	Tightness and excavation support	26·7	13·8	66·5	916·1

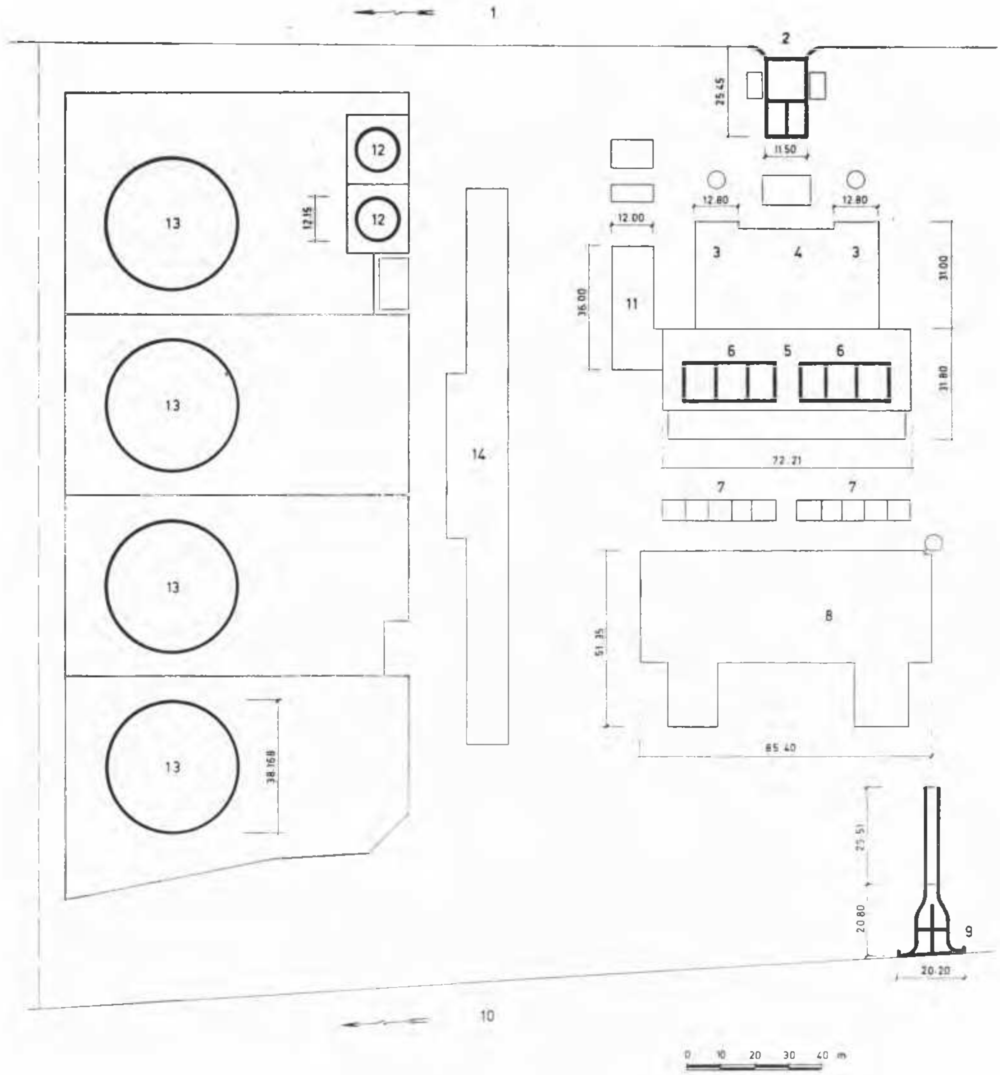

Fig. 10 Porto Corsini thermal power station: Schematic layout (partial) showing the diaphragms in place (heavy black lines).

1. Corsini intake canal; 2. Intake structure; 3. Boilers; 4. Thermal control room; 5. Machine Hall; 6. 78 000 kVA turbine-generating unit; 7. Transformer bay; 8. 130 kV cage; 9. Outlet works; 10. Outlet canal; 11. Direction; 12. Floating-roof, 1 000 cu. m measurement tank; 13. Floating-roof, 15 000 cu. m fuel-oil container tank; 14. Mechanical workshop, store rooms.

Usine thermo-électrique de Porto Corsini : Plan schématique partiel montrant les diaphragmes en place (traits gras).

1. Canal d'amenée; 2. Structure de l'amenée; 3. Chaudières; 4. Chambre de contrôle thermique; 5. Hall des machines; 6. Turbine génératrice de 78 000 kW; 7. Transformateur; 8. Poste de 130 kW; 9. Ouvrage d'évacuation; 10. Canal de fuite; 11. Direction; 12. Réservoir à toit flottant de 1 000 m^3; 13. Réservoir à toit flottant de 15 000 m^3 de fuel-oil; 14. Magasin, atelier mécanique.