Associazione Geotecnica Italiana

Deformation of soils and displacements calculation
X E.C.S.M.F.E.

Proceedings of the
tenth European Conference on Soil Mechanics and Foundation Engineering
Florence, 26-30 may 1991

Settlement analysis of main buildings in power plants by means of 2-D and 3-D models

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ABSTRACT: this research was undertaken with the aid of the considerable amount of data and measurements gathered by ENEL (*) during the construction and working lives of some of its power plants. The study also aims at evaluating how the predictions based on some currently available calculation methods relate to the actual behaviour of such structures, giving an a posteriori evaluation of the reliability of these methods. The structural characteristics of power plant buildings can be described as rigid, flexible or intermediate interaction models. The research includes both geotechnical characterization of foundation soils and settlement analysis by means of 2-D and 3-D models. Comparison between calculation results and the large amount of settlement measurements allowed both evaluation of the degree of reliability of the methodologies presented, when applied to design, and identification of which factors mainly affect the correct prediction of building behaviour vs. time.

RESUME: la grande quantité de données et de mesures recueillies par ENEL (*) pendant la construction et la gestion de centrales de chauffage a été utilisée pour évaluer la concordance entre le comportement réel des principales oeuvres de ces centrales et les prévisions réalisables avec les méthodologies de calcul actuellement disponibles. On a pu vérifier aussi la validité de ces prévisions a posteriori. Les caractéristiques structurales des oeuvres peuvent être schematisées par de modèles d'interaction de type rigide, flexible ou intermédiare. L'étude comprend la caractérisation géotechnique des terrains de fondation et le calcul des tassements obtenus par differents modèlages à 2-D et 3-D. La comparaison des résultats des calculs et des mesures des tassements, au long de plusieurs années, a permis d'évaluer l'applicabilité des méthodologies utilisées au niveau du projet et d'envisager quelques facteurs qui influencent l'exactitude des prévisions du comportement des oeuvres.

1 INTRODUCTION

ENEL carefully monitors the geotechnical and topographic characteristics of its power plants, during both their construction and their working lives, in order to check how the structures react to the evolution of absolute and differential settlements. The consequent amount of data, gathered over the last 20 years on some plants built along the Po river, suggested research aimed at evaluating how the actual behaviour of the structures relates to predictions obtained with the aid of some currently available calculation methods, and at the same time identifying the factors which mainly influence the correctness of the prediction design itself.

All power plants built by ENEL along the Po valley are substantially similar in lay-out, although chimneys, tanks, turbogenerator and boiler supporting structures, and turbine hangars are main structures which widely differ in their structural and geotechnical characterization.

Tanks, which usually have shallow foundations, can be regarded as perfectly flexible structures, whereas chimneys and turbogenerator supporting structures, often have deep foundations and geometric-structural characteristics by which they can be recognized as perfectly stiff structures. Both turbine hangars and boiler supporting structures may be considered as stuctures of intermediate stiffness.

In relation to the working requirements of the machinery, designers indicate 1/1000 as the maximum allowable angular distorsion for all main plant structures. However, tanks can go beyond this limit, the allowable absolute and differential settlements being much higher.

The need to contain settlements and distorsions within required limits has meant that structures were designed with both shallow and deep foundations and with very thick, that is, quite stiff, mats and footings. In some cases the top soil layer was changed; in others its quality was improved by vibroflotation.

(*) Italian national electricity board.

2 GEOTECHNICAL CHARACTERIZATION

The soils on which the Po valley power plants are founded show remarkable stratigraphic heterogeneity and are composed of cohesive and granular materials layered in more or less dense sequences. All geotechnical parameters used in the various calculations were determined on the basis of conventional field and laboratory testing (i.e. analysis of good quality and undisturbed borehole samples, penetration tests by means of mechanical and electric cones, triaxial consolidated and unconsolidated isotropic tests, oedometric tests).

In cohesive soils, deformability undrained modulus E_u was determined by taking into account its relationship with undrained soil shear strength C_u, overconsolidation ratio OCR, plasticity index I_p (Duncan & Buchignani 1976), static penetrometer cone resistance (Sanglerat 1979) and the results of triaxial tests.

In granular soils, deformability drained modulus E was determined by using its empirical relationship with penetrometer cone resistance Q_c (Baldi et al 1982, Robertson & Campanella 1983, Webb et al 1982); in cohesive soils it was determined on the basis of both consolidated triaxial and oedometric tests.

Consolidation and permeability coefficients used in calculations were all determined according to oedometric tests.

3 CALCULATION METHODS USED

Factors ruling the time rate behaviour of soil-founded structures are fundamentally the following (Lewis & Tran 1989):

- slip and differential settlement along soil-structure interfaces;
- strictly non-linear behaviour of soil, with reference to stress and strain;
- the evolutionary nature of consolidation, due to time rate dissipation of pore pressures;
- effects of mutual interaction between soil and structures, which consist in continuous redistribu-

tions of stress, in both soil and structure;
- effects of mutual interaction among adjacent structures;
- chronological sequences of loading phases.

Interaction problems can be analysed by means of coupled and uncoupled calculation methods. In the case presented here, three models were systematically developed and used, two of which belong to the uncoupled model class and one to the coupled model class. Implementation of the first two methods was made in calculation programs called EDOM and FIESTA/EDOM, while the OMEGA calculation program was used for the third method.

Each program models the following: time rate settlement development (soil consolidation); loading phases and evolution of building construction; mutual influence of adjacent structures; non-linear behaviour of soils during consolidation.

Consolidation analysis in EDOM and FIESTA/EDOM was performed by means of mathematical modelling based on Terzaghi's monodimensional theory expanded to a horizontal multilayered stratum (Schiffman & Arya 1977); geotechnical soil characteristics are assumed to be different in each layer; at any time total settlement is the sum of immediate settlement plus oedometric consolidation settlement.

Settlement calculation calls for analysis of load-induced soil stress, which in this case was evaluated according to two different approaches.

In the first approach (EDOM program), the foundation structures can be modelled as "infinitely rigid or flexible" on an elastic, homogeneous and isotropic half-space (Boussinesq solution).

In the second approach (FIESTA/EDOM program), foundation structures and soil are modelled through a 3-D finite element analysis (Babuska et al. 1981, Peano 1976), in which it is assumed that the materials have linear elastic behaviour. Soil is treated as an isotropic but non-homogeneous medium which, in accordance with test evidence, has a deformability modulus increasing with depth.

The OMEGA code (Fusco 1985) is capable of modelling the same factors as those of the EDOM and FIESTA/EDOM programs. The substantial difference between the OMEGA and the other programs is theoretical correctness: at any time OMEGA can simultaneously satisfy all concurring equations together with boundary conditions. Consolidation is analyzed through the Biot three-dimensional theory (Biot 1941). A complete problem definition requires the identification of constitutive laws ruling structures and soil behaviour, permeability characteristics of soil, geometry of the domains examined, and boundary conditions on both displacements and neutral pressures.

FIESTA/EDOM and OMEGA have an advantage over EDOM: they can conveniently model foundation structures and soils with reference to their geometries and stiffnesses.

4 SOIL AND FOUNDATION STRUCTURE MODELLING

Finite element modelling of all recognized layers in the stratigraphic sequences of the examined sites was found to be difficult and exceedingly time-consuming. Time investment can be particularly large in two cases: first, when analysis must be conducted with the aid of coupled methods of calculation in which, as known, cohesive layers need the mesh to be thickened near the draining surfaces in order to represent pore pressure evolution better (Reed 1984); second, when three-dimensional uncoupled stress and strain analysis is required.

The original stratigraphy was therefore modelled by compacting groups of recognized layers into a smaller number of equivalent layers.

Compaction of a certain number of layers with different chracteristics into one equivalent stratum was made by assuming that stress is constant within the original layers and that such layers behave like a serial combination. Similar arguments led to the identification of the equivalent stratum permeability.

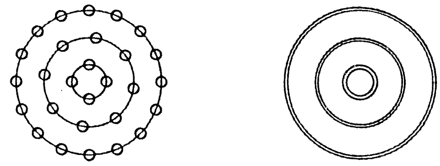


Figure 1. Scheme for piles spaced in circles.

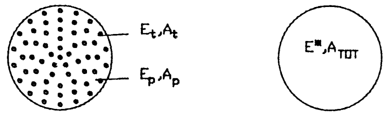


Figure 2. Scheme for thickly distributed piles.

With reference to 3-D finite element modelling of deep foundation structures, calculation time was kept within acceptable limits by using simplified models for the three-dimensional distribution of structures in space.

Piles spaced in circles were represented, in horizontal projection, by means of an annulus for each circle (figure 1) with an area equal to the sum of the areas of all the piles in that circle, and an average diameter equal to the diameter of that circle (Presley & Poulos 1986).

Where piles were thickly distributed, the above method would have required a far too burdensome discretization; an acceptable method was found to be that treating the volume defined by the piles as an homogeneous material and evaluating the equivalent stiffness as a parallel combination of piles and included soil (figure 2).

5 SOME RESULTS OF CALCULATIONS

Calculation and analysis were carried out on time rate of settlements of some buildings and structures belonging to four power stations in the Po valley, and an extremely large amount of data was correspondingly processed. The exemplification results shown here refer to the Ostiglia power plant.

This plant is composed of four 320 MW oil-fired units, one turbine hangar and two utility buildings. The three chimneys are 120, 170 and 200 m high; seven of the nine oil storage tanks have a capacity of 50,000 m^3, while the remaining two hold 100,000 m^3.

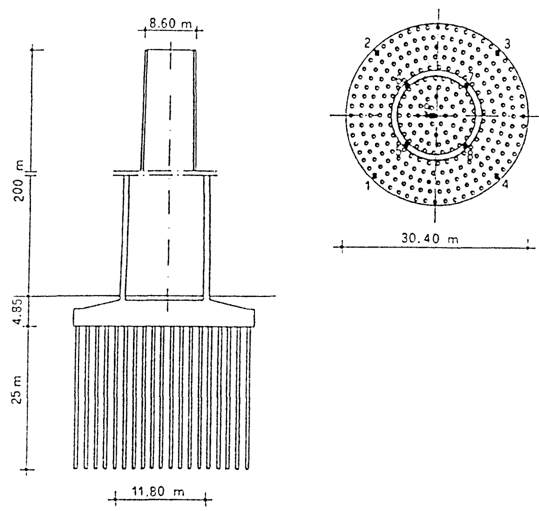


Figure 3: Ostiglia power plant: group 3-4 chimney - geometrical characteristics of chimney and soil profile.

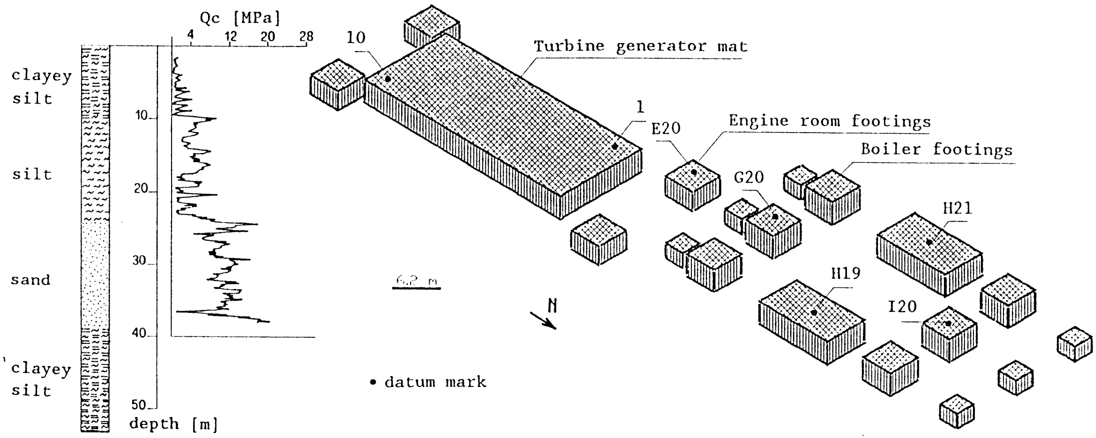
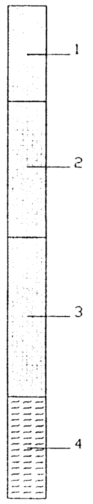


Figure 4 . Ostiglia power plant: group n. 4
- geometrical characteristics of foundations and soil profile.



LAYER N.	TICHNESS [m]	DEPTH [m]	SAMPLE	SUBMERGED UNIT WEIGHT [kN/m³]	UNDRAINED MODULUS [MPa]	DRAINED MODULUS ROOF [MPa]	DRAINED MODULUS BASE [MPa]	POISSON COEFFICENT
1	10.0	10.0		9.0		30.0	45.0	.30
2	14.0	24.0		9.0		45.0	65.0	.30
3	17.0	41.0		9.0		65.0	90.0	.30
4	10.0	51.0	4	9.0	150.0			.30

sandy soils

clayey soils

OEDOMETRIC CURVES

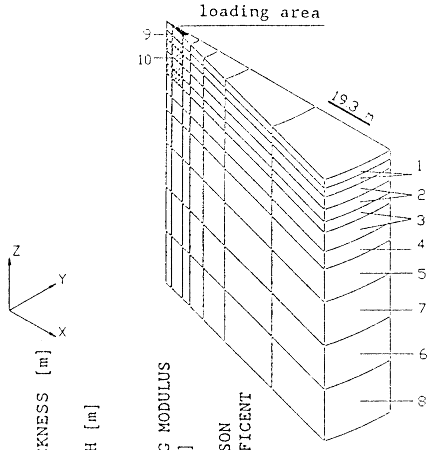
SAMPLE 4

Cv [m²/s] $8.0 \cdot 10^{-8}$

σ [MPa]	e
0.052	0.748
0.104	0.736
0.260	0.703
0.520	0.675
1.040	0.639
0.520	0.642
0.260	0.646
0.052	0.659

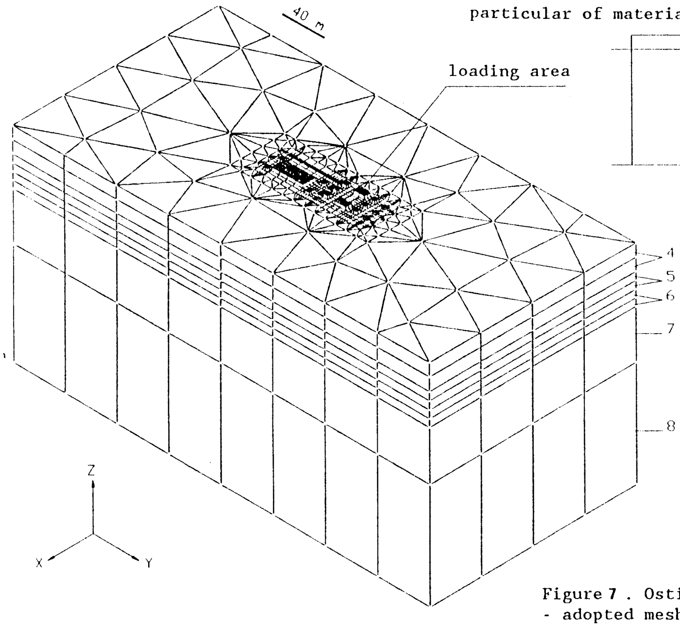
Figure 5 . Ostiglia power plant:
- adopted scheme and material parameters (EDOM).

The following descriptions and measurements refer to the chimney of units 3 and 4 and to the main plant structures of unit 4.
The chimney of units 3 and 4 (figure 3) is 200 m high, its bottom diameter is 11.80 m and its upper diameter 8.60 m. It is founded on 281 Franki piles, 0.52 m in diameter and 25 m in length, which are connected at the top by a circular mat 30.4 m in diameter and 4.25 m in thickness.
The main structures of unit 4 include: the metallic frame supporting the boiler, founded on Franki piles, again 0.52 m wide and 25 m long, but connected at the top by footings of various sizes; the reinforced concrete frame supporting the turbine-generator, founded on a mat of 12.40 x 30.00 x 3.00 m on the above described Franki piles; the metal portals of the turbine hangar which, with a 40.00 m air gap, are also founded on Franki piles connected at the top by footings.
Figure 4 shows the planimetric disposition of the foundations, the location of bench-marks to measure settlements, and a soil stratigraphic profile beside a typical cone resistance diagram.
Figure 5 shows foundation soil stratigraphy and geotechnical parameters, used in EDOM for settlement calculation.
Figures 6 and 7 show the materials and elasticity parameters used in FIESTA for finite element calculation of the chimney of units 3 and 4, and of the structures of unit 4.
Figure 8 shows calculation modelling and geotechnical parameters used in OMEGA.
All results can be found in figures 9 to 12.
In particular, figure 9 shows the comparison between calculated and measured settlements of the chimney of

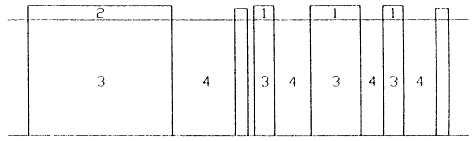


MATERIAL N.	THICKNESS [m]	DEPTH [m]	YOUNG MODULUS [MPa]	POISSON COEFFICENT
1	10.0	10.0	40.0	.30
2	14.0	24.0	55.0	.30
3	17.0	41.0	80.0	.30
4	10.0	51.0	150.0	.35
5	19.0	70.0	120.0	.30
6	25.0	95.0	150.0	.30
7	25.0	120.0	190.0	.30
8	30.0	150.0	230.0	.30
9	5.0		25000.0	.10
10	25.0		2100.0	.20

Figure 6. Ostiglia power plant: chimney of group n. 3-4
- adopted mesh and material parameters (FIESTA).



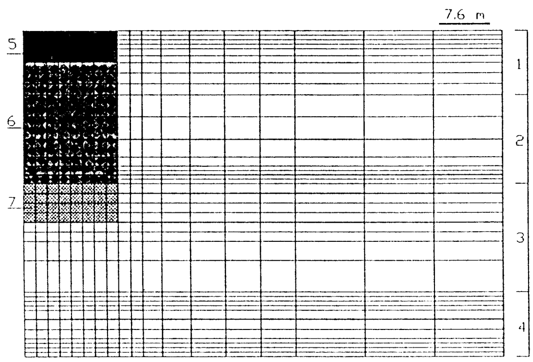
particular of materials distribution in the foundation zone



MATERIAL N.	THICKNESS [m]	DEPTH [m]	YOUNG MODULUS [MPa]	POISSON COEFFICENT
1	2.4		25000.0	.20
2	3.0		25000.0(*) 75000.0(+)	.20
3	24.0	24.0	2000.0	.10
4	24.0	24.0	45.0	.30
5	15.0	39.0	80.0	.30
6	14.3	53.3	150.0	.35
7	46.7	100.0	140.0	.30
8	100.0	200.0	235.0	.30

(*) $E_x = E_z$
(+) E_y

Figure 7 . Ostiglia power plant: group n. 4 - adopted mesh and material parameters (FIESTA).



MATERIAL N.	TICHNESS [m]	DEPTH [m]	YOUNG MODULUS [MPa]	POISSON COEFFICENT	PERMEABILITY COEFFICENT [m/s]
1	10.0	10.0	5.0	.30	$1.0 \cdot 10^{-9}$
2	14.0	24.0	6.0	.30	$1.0 \cdot 10^{-8}$
3	17.0	41.0	75.0	.35	$1.0 \cdot 10^{-6}$
4	10.0	51.0	15.0	.30	$1.0 \cdot 10^{-9}$
5			25000.0	.10	$1.0 \cdot 10^{-9}$
6			2000.0	.20	$1.0 \cdot 10^{-9}$
7			2000.0	.20	$1.0 \cdot 10^{-6}$

Figure 8 . Ostiglia power plant: chimney of group n. 3-4 - adopted mesh and material parameters (OMEGA).

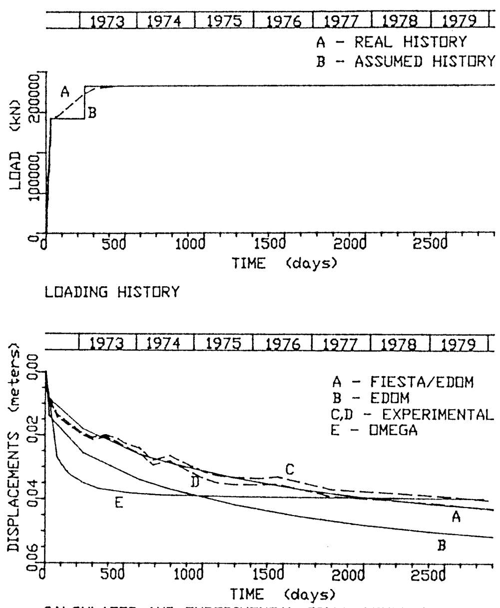


Figure 9 . Ostiglia power plant: chimney of group n. 3-4 - results of calculations.

units 3 and 4. According to the reported curves, FIESTA/EDOM calculation best fits reality in the settlement time rate prediction; instead, EDOM calculation forecasts larger settlements than reality, due to uncertainties in positioning and dimensioning the equivalent footing; on one hand, OMEGA calculation achieves results on final settlements which fit the real measurements, but on the other, it fails to make an exact time rate prediction, probably as a consequence of incorrect evaluation of permeability coefficient k and of the inadequacy of the linear elastic constitutive law.

Figures 10 and 11 show the comparison between calculated and measured settlements of some survey points in the unit 4 structures. With reference to turbine-generator settlements, the reported results indicate that FIESTA/EDOM makes better prediction than EDOM, probably due to the fact that only the first method reckons the considerable stiffness of the turbine-generator foundation mat. With reference to the settlements of both the boiler and the turbine hangar, good results can be achieved both ways, as the foundations are based on isolated footings, which are flexible when taken all together.

Figure 12 shows settlement contour lines calculated by means of both EDOM and FIESTA/EDOM; as shown, the contour lines of the two methods tend to coincide in the areas where the foundations are based on isolated footings, while they part in the rigid area of the turbine-generator where EDOM, making use of flexible loaded areas, forecasts larger settlements.

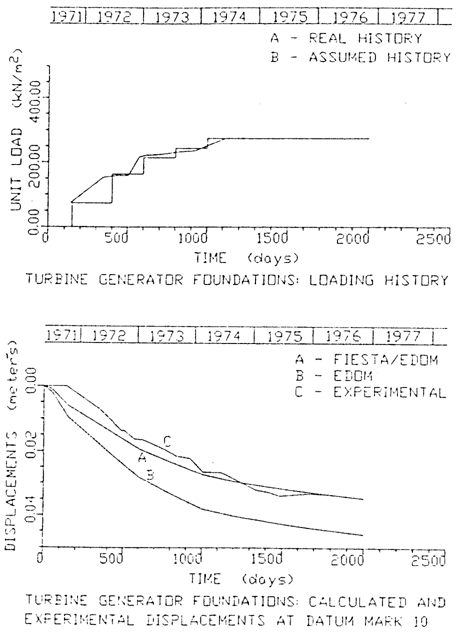


Figure 10. Ostiglia power plant: group n. 4 results of calculations.

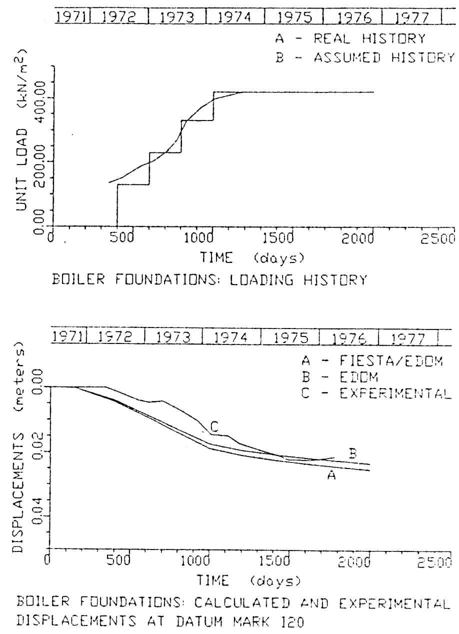


Figure 11. Ostiglia power plant: group n. 4 results of calculations.

Table 1. Average settlement (mm) of buildings 4 years after construction.

	unit 2	unit 3	unit 4
boiler	28	33	23
turbine-generator	35	38	34
chimney	30	36	

Table 1 reports average settlements of the buildings of units 2, 3 and 4 four years after construction. The differences (within 1 cm) that can be observed in the settlement of buildings belonging to different units are due both to the different stratigraphy of the soils on which they are founded and to their different foundations. While, for instance, unit 2 is founded on large-diameter bored piles driven to a depth of 33 m, units 3 and 4 are founded on Franki piles at 28 m. Referring to chimneys, while that of unit 2 is founded on large-diameter bored piles driven to a depth of 33 m and has a load concentration of 144 t/m, the chimney of units 3 and 4 is founded on Franki piles at 30 m and has a load concentration of 190 t/m.

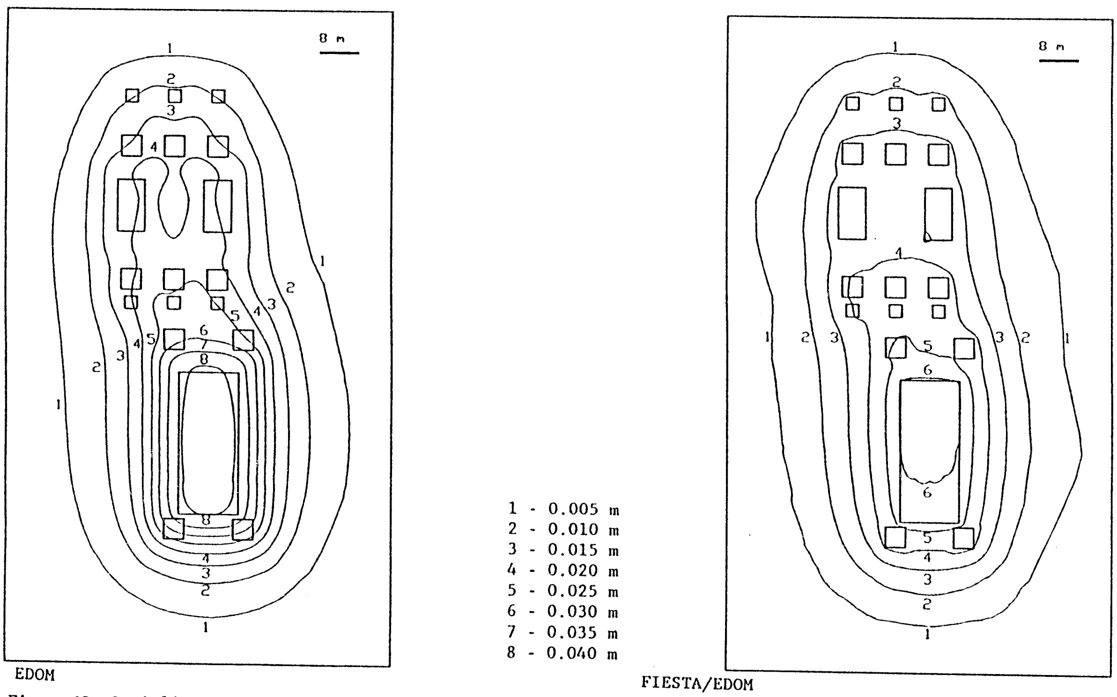


Figure 12. Ostiglia power plant: group n. 4 - displacement contours at time 1000 days.

6 FINAL REMARKS

The analyses developed so far (including those which are not reported here) indicate that, with reference to the settlement of flexible loaded areas (preloadings, tanks and structures with flexible foundations when taken all together), all three of the presented methods provide satisfactory results, although the EDOM program turns out to be the quickest and least expensive.
With reference to the settlement of finite stiffness structures, especially those with deep foundations, the FIESTA/EDOM program, as applied here, provides satisfactory results in spite its simple parameters and its relatively small amount of calculation time.
The OMEGA program is undoubtedly the most exact, but, for the time being, the amount of time it requires for calculation is exceedingly long, and it can only fall within acceptable limits if simple modelling or a linear elastic constitutive law are used: in turn, this constitutive law seldom lead to satisfactory results.
More elaborate constitutive laws for complex modelling cause the amount of time necessary for calculation to increase up to an unacceptable level from the design viewpoint.
The studies carried out also indicated that the correct prediction of building behaviour vs. time is mainly affected by the following factors: careful identification of stratigraphic soil profiles by means of sufficiently deep field tests; definition of geotechnical parameters on the basis of accurate field and laboratory tests on representative samples; stiffness of structures; adequate modelling of deep foundations, also with reference to load test results.

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