Stability conditions in the Larderello area (Italy)

Les conditions de stabilité dans la région de Larderello (Italie)

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SYNOPSIS: A series of multidisciplinary geological, hydrologic, geotechnical and structural studies were carried out in a broad hilly area characterized by poor stability conditions. All the technical data produced by engineering projects, carried out over a 25 year period were re-examined. In critical areas new investigations were performed. In conclusion, a variety of stabilization measures and guidelines for land use planning (including the preservation of the existing settlement and planning of future buildings) have been worked out on the basis of the results produced by this study.

1. INTRODUCTION

Larderello is a modern industrial town in Southern Tuscany (Central Italy) which started to expand in 1818 from a nucleus of residential and industrial buildings which arose around the first factory in the world to promote the industrial use of geothermal energy (De Larderel Concern which gave the name to the town)

Larderello is located at 400 m a.s.l. in the Possera Valley, in the heart of an area of woody and bushy hills.

Ancient prints and early 19th century descriptions show this area to be bleak, scattered with "lagoni" (steaming mud pools) and with strong gas and steam fumaroles ("soffioni").

Early geological descriptions (LOTTI, 1910) suggest that the morphology of the area resulted from large ancient landslides and point to the widespread presence of signs indicating recent or ongoing landslides.

The industrial plants and the residential zones have thus been built in difficult geotechnical conditions where it has been necessary to make radical changes in the original morphology (cuts, fills, etc.).

For instance, in 1842 concrete tilted boilers, some 70 m long were built to extract boric acid from the waters of the "lagoni".

As further knowledge was gained on the potential of geothermal resources, investigations were undertaken to use steam as motive power and the first geothermoelectric power plant was built in 1904.

The industrial area expanded rapidly as steam was increasingly used as energy source.

The results obtained by ENEL-UNG in recent years through its drilling and research activities have led to a project for the renewal of the Larderello area which requires the drilling of new wells and the installation of new geothermoelectric plants. The project requires cuttings (8+10 m high and 10+100 m long), large embankments (up to 8 m high), and the construction of vulnerable facilities on slopes which are slide prone.

Under this project therefore an interdisciplinary investigation of the whole area had to be undertaken to explore the hydrologic, the geological, geotechnical aspects and the structural and static characteristics of existing old buildings.

Geotechnical and Geophysical surveys covering a very wide area were started and the more vulnerable areas stability-wise were closely monitored.

2. GEOLOGICAL SETTING

The knowledge of the general and structural geological situation of the Larderello area is the result of a long series of studies often geared to the interpretation of the geothermal events and to the optimization of exploitation for industrial purposes.

Such studies utilized the information obtained from the countless drillings for the prospection and exploitation of the geothermal fields of a broader region surrounding the area reported in this works.

As to the outcropping soils that are more closely related to the geotechnical aspects of the area, mention can be made of two detailed reports by MAZZANTI (1966) and LAZZAROTTO and MAZZANTI (1965).

The formation that outcrops more extensively is a "Marly-limestone Flysch" of the Middle-Upper Cretaceous, consisting of a rhythmic sequence of limestones, marly limestones and dark grey clays. In the investigated area the overall thickness of the formation is a few hundred metres.

As a result of extensive translational tectonic movements, the formation appears to be highly disarranged (with a dip varying from one zone to another), or totally chaotic; the clay facies presents a typical scaly structure. In the westernmost part of the area, the Flysch formation is overlain by Pliocene clays representing the bedrock of a marine sequence which filled a subsident basin which had formed after distensive tectonic phases in the Apennines starting from the Miocene.

The Pliocene formations are regularly arranged but they contain frequent intercalations or large inclusions of Flysch materials

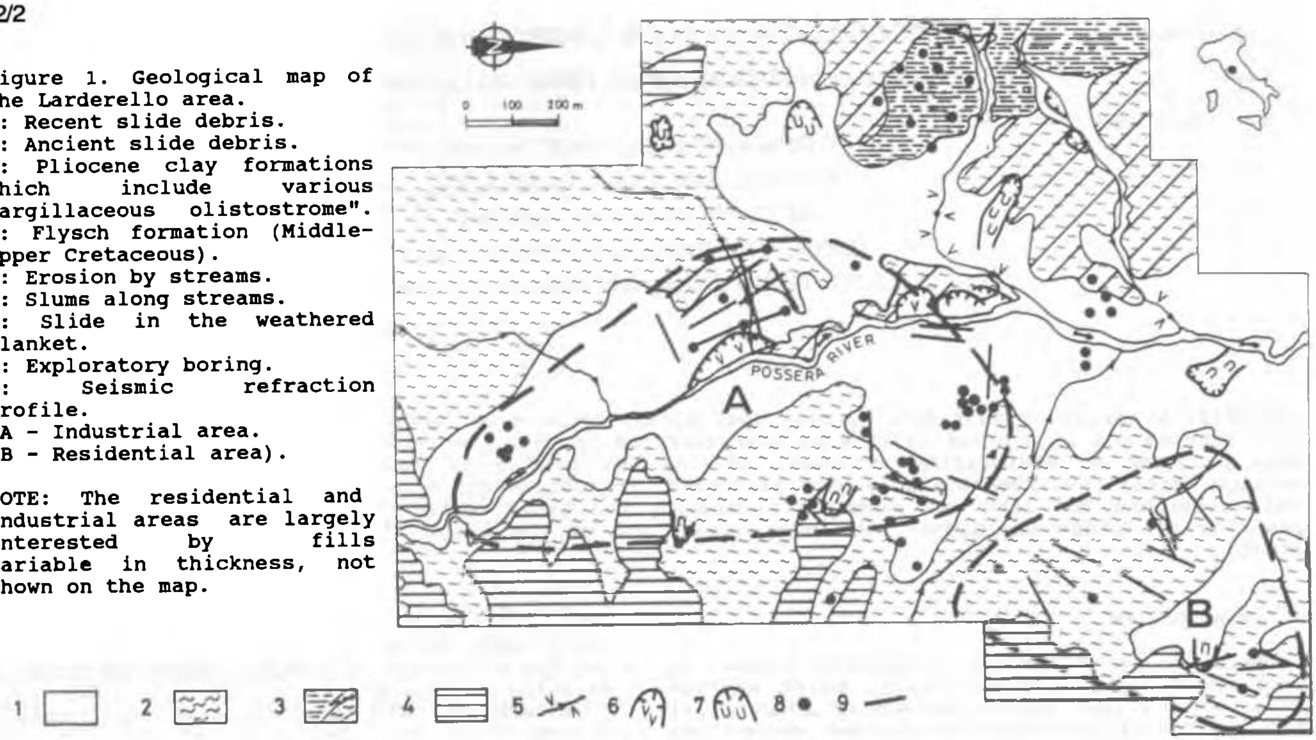

Figure 1. Geological map of the Larderello area.
1: Recent slide debris.
2: Ancient slide debris.
3: Pliocene clay formations which include various "argillaceous olistostrome".
4: Flysch formation (Middle-upper Cretaceous).
5: Erosion by streams.
6: Slums along streams.
7: Slide in the weathered blanket.
8: Exploratory boring.
9: Seismic refraction profile.
(A - Industrial area.
B - Residential area).

NOTE: The residential and industrial areas are largely interested by fills variable in thickness, not shown on the map.

("Olistostromes"), which quite likely slided into the Pliocene basin during the sedimentation of the clays. The Flysch materials are present in small chaotically dispersed fragments in the Olistostromes and the lapideous portions of the original formation have been broken down into small fragments or blocks immersed in a clayey-scaly matrix.

The Flysch formation has undergone massive slides (rotational slides and flows) since ancient times; the resulting slides partially maintain the typical morphology and at present they do not show signs of deep movements.

The present slides involve only the surfacemost weathered layer of the formation (earth slumps and earth flows) and are mostly initiated by the erosion produced by streams.

The morphological evolution and the present stability conditions of the Larderello area are illustrated in Fig.1, where the outcropping soils have been broken down into main types from a geological and geotechnical standpoint keeping in mind their characteristics and their mutual stratigraphic relationships.

The various soils are all covered by a blanket of surface debris varying in thickness from one area to another but which increases towards the valley.

3. INVESTIGATIONS AND MONITORING MEASURES

By means of detailed geological surveys and by a photogeological analysis of aerial photographs taken over the years, zones having different stability conditions have been identified; the geometry and characteristics of the slides have been defined as well as the factors governing the natural behaviour and stability of the slopes.

All the geotechnical data (drilling data, geophysical surveys, laboratory tests performed randomly over the past 25 years for the construction of the industrial and residential buildings) were pooled and re-examined. Additional specific investigations were carried out for critical areas and/or for areas of special interest.

Globally, 80 continuous drillings for over 2500 m and 4500 m of seismic refraction were performed. In the exploratory borings (30+40 m deep) undisturbed samples were taken and Standard Penetration Tests (SPT) were performed. A large number of physico-mechanical tests were carried out in the laboratory to characterize the soils from a geotechnical point of view.

Around 50 piezometers and 15 inclinometers were installed; in the building showing cracks, reference bases were places to measure further movements (opening or closing of the cracks).

The findings of the in situ tests, the laboratory tests and the measurements provided by the monitoring instrumentation were stored in a "data bank".

4. GEOTECHNICAL CHARACTERISTICS OF THE SOILS

The typical geotechnical profiles of the investigated area are illustrated in Fig. 2 Table 1 summarizes the variability range of the main geotechnical parametres of the Pliocene clay formation, of the Flysch, of the Olistostrome and of their surface blanket soils. The geotechnical characteristics of the Pliocene clay formation were found to be rather uniform, even over rather large areas, and they generally varied linearly with depth. On the other hand, the characteristics of the Flysch formation are more variable, even over small areas.

It must be pointed out, that given identical sampling methods and the same laboratory tests, the scaly structure and the frequent rock fragments in the Flysch and in the Olistostrome produce a scatter in the geotechnical data.

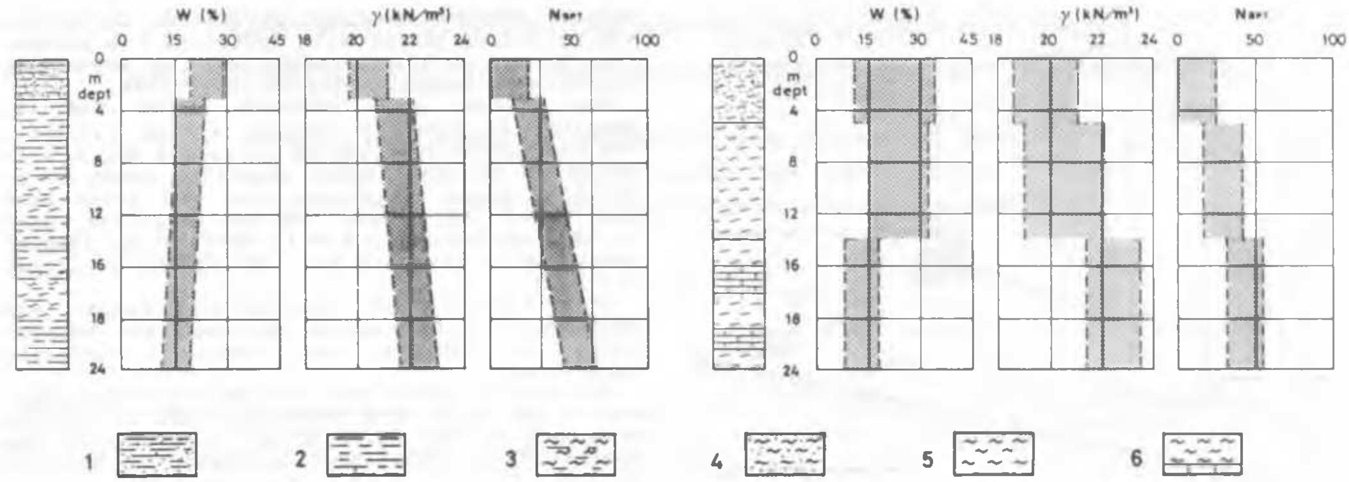

Figure 2. Typical geotechnical profiles of the investigated area. 1: Oxidized and remoulded surface soils (Pliocene). 2: Pliocene clays. 3: Olistostrome. 4: Oxidized and remoulded surface soils. (Flysch). 5: Recent and ancient slide debris. 6: Flysch formation.

In terms of grain size, the Pliocene formation is more homogeneous and can be classified as silts containing clay. The Flysch and the olistostrome, instead, are more heterogeneous and contain plentiful sand and gravel fractions.

The surface soils reflect the nature of the substratum (Flysch or Pliocene clays) from which they derive. The weathered blanket of the Flysch is less heterogeneous than the in situ formation and in particular it contains a smaller proportion of coarse fraction; this is very likely due to the breakdown of the scaley clays as a result of softening and weathering.

The Atterberg limits, determined according to the ASTM procedure, emphasize significant differences between superficial soils and both underlying formations; the gradual passage from the surface blanket to the substratum is dependent on the softening degree of the underlying formations. For the surfacemost soils the Atterberg limits are always higher. Such differences reflect changes in the mineralogical composition which have occurred in the soils as a results of weathering and remoulding.

Table 1. Geotechnical properties.

	A1	A2	A3	B1	B2	B3	B4
Wl [%]	40-60	30-45	30-40	35-65	40-65	35-50	30-45
Wp [%]	20-35	15-25	15-20	15-45	15-25	10-30	10-25
γs [kN/m3]		27.2-27.5			27.0-27.3		
W [%]	20-25	14-22	14-15	8-35	20-40	15-25	10-20
C.I. [%]	.9- >1	>1	>1	.7- >1	.9- >1	.9- >1	>1
γ [kN/m3]	20.-21.	21.-22.	22.-22.	19.-21.	18.-21.	20.-22.	22.-23.
C' [kPa]	0-10	20-40	-	0-10	0-10	0-10	40
φ [-]	18-21	26-30	-	18-25	20-27	20-27	33
$φ_r$ [-]	-	-	-		18-25		-
Cc [-]	.17-.22	.10-.18	-		.21-.31		-
Cs [-]	.06-.08	.05-.07	-		.07-.09		-
Vp [Km/s]	-	-	-	0.4-0.7	0.6-0.8	1.2-1.9	2.4-2.7

A1 Pliocene surface soils. A2 Pliocene clays. A3 Olistostrome.
B1 Flysch surface soils. B2 Recent slide debris. B3 Ancient slide debris.
B4 Flysch formation

The strength characteristics of the soils were determined by both SPT and laboratory tests (shear and triaxial tests). The residual strength values were determined by reversal shear tests (4÷5 cycles).

In the areas where the Pliocene formation outcrops, a marked difference in strength characteristics between substratum and superficial soils was found. On the contrary, for the Flysch the differences are less evident because of the grain size heterogeneity in the various samples.

5. STABILITY CONDITIONS

In geological eras slope evolution was governed by major landslides; slide debris became mostly stabilized in time but the surfacemost layers were weathered and remoulded; locally some slope sections which were in limit equilibrium conditions were repeatedly subjected to landslides involving the surfacemost soils, for maximum depths of 5÷8 m, whose mechanical characteristics were poorer than those of the underlying in situ formations.

Past experience has shown that the instability effects (observed on the soils and on the buildings of Larderello) are localized, and they do not produce instability in the whole of the slope.

The investigations, the monitoring and computer verifications carried out in the area have shown that the factors which have a greater influence on stability are the heightening of the groundwater level and local changes in slope gradient. Even slight changes in these values may jeopardize the stability of slope portions.

At present, as in the last 100-150 years, changes in slope profile can be traced back partially to the intense erosion of streams and partially to the development works required for the industrial and human settlement (roads, buildings, yards, etc.).

Data from previous observations and the experience acquired on past events and on the causes producing the slides have all been used to design stabilization measures which are to secure suitable safety margins (η>1.3) for future buildings.

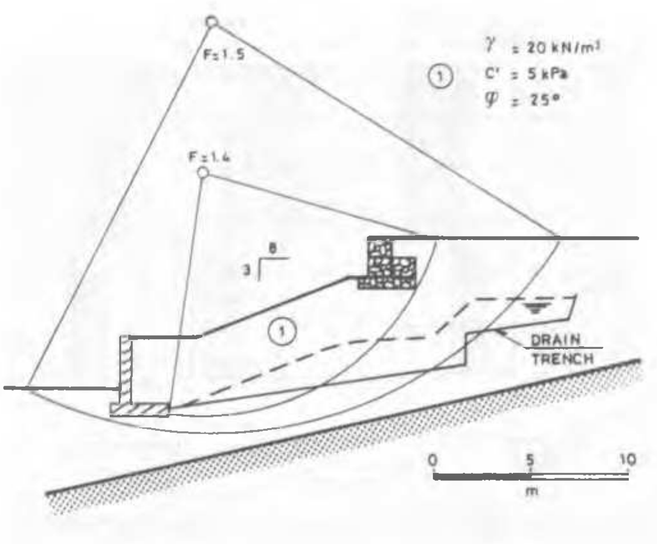

Figure 3. Local stability analyses after remedial measures.

The increased sizes of the plants to be built and the non optimal stability conditions of the areas eligible for building demand more expensive measures than those adopted in the past.

Taking into account the local and global stability conditions, the measures were designed by means of computer programs (GEONS and STABL2) (BARLA et al., 1974 and BOUTRUP et al., 1979).

Two significant examples of the examined situations are given. Fig. 3 shows a schematic section of the measures adopted to widen an existing yard. Local stability is secured by drains and by rigid and flexible support structures.

Fig. 4 shows an area where a new geothermoelectric plant is to be built. Computer verifications of stability have shown that there are no problems of global stability. On the contrary local stability demands the adoption of measures such as deep drains, pilings, etc.

6. GEOTECHNICAL SITUATION OF THE AREA

Three main zones were defined (Fig.1).

The first (recent slide debris), is the gently sloping valley bed area where the thickness of the weathered soil reaches the highest values (10+15 m) and where the main cause for instability is the erosion produced by the stream. Besides adopting structures protecting the area from the erosive action of the stream, the future buildings will have to have deep foundations independently of their size.

The second zone (ancient slide debris), consists of slightly steeper slopes (10+20%), the overburden soil varies between 2 and 8 m in thickness and here local stability needs to be verified where artificial cuts and yards have been built. As regards the new buildings, deep or shallow foundations will have to be adopted depending on the size and load of the buildings involved.

Stabilization of excavation faces and embankments will require drainage and support works to improve the previous stability conditions.

The same criteria hold for the built-up areas; during the study the buildings were classified according a risk scale which, depending on the degree of vulnerability, provided the data to set up a list of priority interventions.

The third zone is characterized by steeper slopes (>20+30%) where the in situ formation is located at small depths and is covered by weathered blanket soils of small thickness.

In the past, in this zone the number of building sites, was rather limited and given the present and future need for new building sites, it is necessary to carefully study the stability conditions of artificial cuts, taking into account the high degree of variability of the rock-clay ratio in the Flyschoid formation.

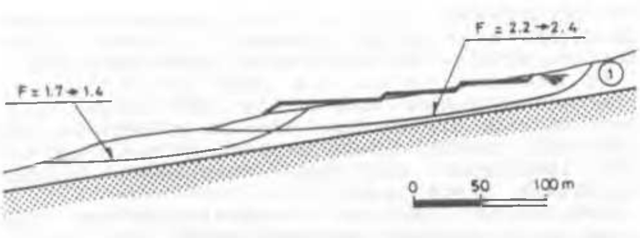

Figure 4. Global stability analyses in an area where a geothermoelectric power plant is to be built.

7. CONCLUSIONS

The series of investigations carried out entailed, a close study of the geological-geotechnical and hydraulic-hydrologic instability phenomena as well as a structural study of the existing buildings.

The results obtained for the various aspects were processed taking into account the interaction of the causes responsible for the instability phenomena that have left noticeable traces in the buildings over the last century.

The data and observations made in the past, supplemented with additional investigations, have served to define the guidelines being followed in area use related to the need to preserve existing and prospective settlements.

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