Consolidation of the Historical Cities of San Leo and Orvieto

Consolidation des Villes Historiques de S. Leo et Orvieto

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SYNOPSIS The report, after a brief geological description of the areas, describes the basic mechanics of the rocky failures of two localities of peculiar historical and artistic interest: the Rocca of St. Leo in Romagna and the town of Orvieto in Umbria, as well as the methods applied to prevent rockfalls and for the stabilization of the cliffs.
The instability of the cliffs is in both cases due to the geomechanics characteristics of the bed rock formations on which the cliffs rise, as well as to the natural exogenous agents and to the men's action (cut of vegetation, loss of water of the hydric and sevage plants ect.). The methods for improving the stability of of the cliffs considered regard the removal or the limitation of the causes of the failures and the recostitution of the original equilibrium of cliffs.
The methods, described from the design to the pratical application, are the following:
- reduction of the teorethical cliff height with prestressed anchors;
- drainage of the slope in the bed strata;
- use of gabions and reinforced concrete diaphragm walls to prevent the erosion of the slope and to buttres the slope;
- reinforcement of the cliff with rock-bolts patterns associated with very long prestressed anchorages;
- horizontal and subvertical drains to reduce water pressure;
- revision of the hydraulic and sevage plants.

FOREWORD

The towns of St. Leo and Orvieto are typical of a kind of Italian sites that, located in high position and with abundant water resources, have had in the past great strategical importance. These sites have many points in common, as they are located on rocky plates, limited by subvertical walls and hence suitable for defense with little effort.
The almost uninterrupted presence of man in these sites since the VIII - VI century B.C. is demonstrated by a number of archeological findings and historical monuments.
The morphology, the nature and the condition of the ground, the exogenous agents and sometimes the presence of man, have resulted in many of these towns having been subject, and being subject even today, to more or less serious rocky failures.

GENERALITY

The two sites are basically subject to extended failures in the cliffs and in the surrounding slopes. The typology of these failures, notwithstanding the different geological nature of the plates, is similar in the two cases.
Actually the nature of the soil, underlaying the two cliffs, results in flow landslides, which are the primary causes of the anomolous tensions in the overlaying rocky formations, with the consequence of toppling failures at more or less regular intervals.
Both cliffs are characterized by the almost complete removal, at their bottom, of the natural vegetation. The slopes of the bed strata are, in both cases, at their natural limit.
The ditches, which are layed out radially in the case of Orvieto and encompass the cliff in the case of St. Leo, are supplied by water of both meteoric and sewage plant origin; they have not reached the equilibrium profile and thus show a very rapid erosion that reaches up to the bottom of the cliff.
The existence of a large collection of hystorical data, has made it possible to reconstruct the time evolution of failure also in relation to the presence of man and to the changes brought about by him.
This is particulary the case of Orvieto because of the plentyful iconographic material.
The consolidation and strengthening works are similar for the two cases and obtain the recovery of the sites according to the following lines:

- removal of the causes of the failures
- stabilization of the walls of the cliff and of the slopes at the bottom, where the failures occur.

Therefore a preliminary investigation was started in order to:

- obtain a complete geological and geotechnical picture of the continuous and increasing deterioration of the two sites, also in order to define the boundary of the intervention;
- make an assessment, knowing the hystorical evolution of the progress of the failures, of the real influence of man's presence;
- make the proposal for the recovery and in particular establish the priorities in the project.

Furthermore, in studying the consolidation projects, a great attention was given to the problem of the conservation of natural environment of the two cities, because of their great value both with regard to hystory and landscape.
The above projects are now under way both in Orvieto and St. Leo (August 1980).

ST. LEO SITE

Geomorphology

The site of St. Leo has a square shape bounded by subvertical cliffs, more than 80 meters high; its perimeter is about 3,5 Km. and the top surface slopes downwards from East to West. There are two peaks, on the highest and steepest of which the famous Fortezza is located.
The rocky plate is surrounded by two deep valleys in the clay formation.
On the bottom of the ditches there is a layer constituted by degraded and remolded clays. Detritus and boulders coming from the failures in the cliff are included in the upper layers.
The rocky plate is constituted by a fossiliferous limestone, turning gradually, going towards the top, into sandy limestones and calcareous-sandstones (Langhiano).
The gradual lithological transformation is paralleled by a gradual transformation of the type of layer from homogeneous (limestone) to stratified (sandstone).
Limestones are fractured to an intermediate degre, with fractures, sometimes open, having various orientations.
On the contrary, sandstones, which have a West-South West immersion, are heavily fractured according to planes normal to the stratification in direction parallel to the stratification planes.
The bedrock is constituted by stiff clays hardned by diagenesis, which is divided in weakly bound.
The surface layer is remolded and therefore reduced to a clay mass having poor consistency.
The position of the sandstone-limestone complex over the argille scagliose is merely due to tectonics.

Failures

The site of St. Leo has two types of failures:

- flow landslides in the clay formation surrounding the cliff;
- toppling failures in the sandstone-limestone formation.

The phenomenology of the failures may be summed up in the following way: the clay soil due to the meteoric water softens giving rise, at regular intervals of time, to a rotational slip, unveiling the overlaying limestone formation. Reduction of the forces acting at the bottom of the cliff and deterioration in the geomechanical conditions of the clays, results in tensile stresses in the sandstone-limestone complex, such that traction fractures are formed. These traction fractures together with the already existing fractures, determing favourable conditions for failures.
The water in the fractures, which normally is drained through the existing fissures, rising to considerable amounts during heavy rainstorms or the melting of snows, can determine an increase of the traction area and bring the hydrostatic pressure to critical value resulting in the failure of the rocks.

Strengthening operation

A detailed survey was carried out in order to obtain, besides the parameters necessary to determine the type and the dimension of the components of the project, also the areas having priority in the project.
The works aimed at the removal of the causes of the failures and to the recovery of the areas, are basically constituted by retaining structures, hydraulic works, remodelling of surfaces, reafforestation in the area of "argille scagliose".
For the limestone-sandstone formation the recovery of the walls was planned by the following means:pretensioned anchorages, connected with a dense surface net of steel nails, cleaning of the fractures with water and air, filing the fractures with cement injections, removal of hydrostatic pressure by means of subhorizontal microdrainages.

Slopes

The intensity of the acting forces and the impossibility of avoiding settlements, which could be considerable considering the nature of the soil, has led to the utilization of flexible structures (gabions), both for the stabilization and for the drainage of the slopes.
Therefore the dimensioning and the localization of the above structures was planned so that the residual movement of the landslide could be absorbed, allowing the material to penetrate in between the various elements forming the whole structure. Thus the gradual compression of the soil and the removal of water, drained away, results in the consolidation of the clay.
In addition and complement of the above mentioned retaining structures, the project foresees the hydraulic arrangement of the whole area, the remodelling and the reafforestation of the slopes. This remedial measures will limit or avoid the free flow of the meteoric waters, therefore reducing the moisture content of the surface strata and achieving a substantial improvement in stress-resisting properties of the soil.

Rocky plate

The works, that up to date have been finished, regard the area underlaying the gate of the town, while the works on the N-NE site just below the keep of the Fortress are still running.
On the first site considered the rock appears heavily and various fractured.
These discontinuities, that extend very deep inside the rock cliff, demonstrate a state of general release, they can be divided in two main systems, the first is almost subvertical and the second one is little sloping on the horizont.
The project foresees the anchorage into the deep sound strata of the external cortical strata (5÷10 m thickness), where the failures occur, in the following way.
A general consolidation of the external surface of the cliff is first carried out using dense net of the steel nails and cement injection. In this way the single rocky elements divided by the fracture, are connected each other and is possible to avoid a release of the mass along the

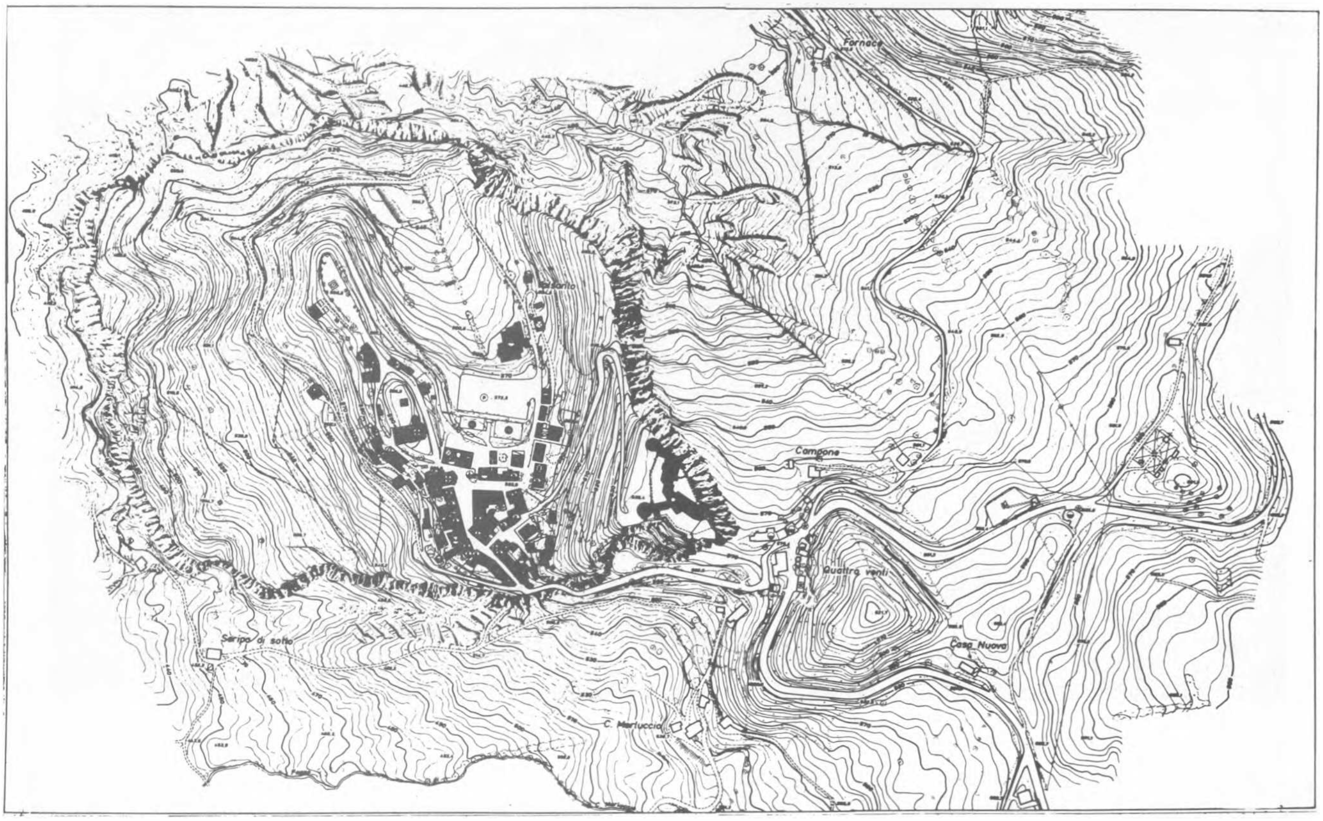


Fig. 1 – St. Leo map of the site – Main failure systems occur in the East and South side.

joints, and the following toppling failure; on this sound cortical rocky volume, afterward the necessary retaining stresses, are applied using pretensional deep steel anchorages.

A carefull survey of the joint sets, meet during the boring operations, was carried out in order to modify, where necessary, the design according to the real situation. The strengthening operation are carried out with the following procedure:

1 – construction of the working bridge (80÷90 m high)
2 – construction of a first series of test anchorages in order to obtain all the necessary data about the rock conditions and to determine the characteristics of the anchorages;
3 – construction of a net of steel nails and consolidation of the surface rock strata with grouting and/or cement injections;
4 – construction of the anchorages;
5 – construction of the microdrainage system.

The surface nails, with a length between 6÷9 m, are formed by high tensile steel bars (30 mm. dia), cemented in 60 mm. dia holes. The direction of the single bars are located in order to form a net and to stich together at least two rock elements. For the grouting the maximum sand size was 2 mm.,the cement content twice that of the sand and the water/cement ratio is about approximately 0,5, special admixtures were used in order to avoid mortar shrinkage. During this operation all the open fractures in the rocks have been cleaned and grouted and all the visible open joints have been sealed in order to avoid any loss of grout during the following injections.

The maximum injection pressure was 2,5 atm.,value careful considered in order to avoid during this stage any additional stress on the outside part of the cliff.

After the grouting every outside loss of grout was carefully washed away with clean water.

Ther permanent anchors have the following characteristics:
average length 35,00 m;
maximum length 55,00 m;
carrying capacity 45,00 ton;
hole 100 mm. dia.

The drilling operation were carried on using in the first works (1969–70) normal air compressed percussion drilling with air lift than in the following works (1979–80) down the hole hammers with a good increase in the daily production.

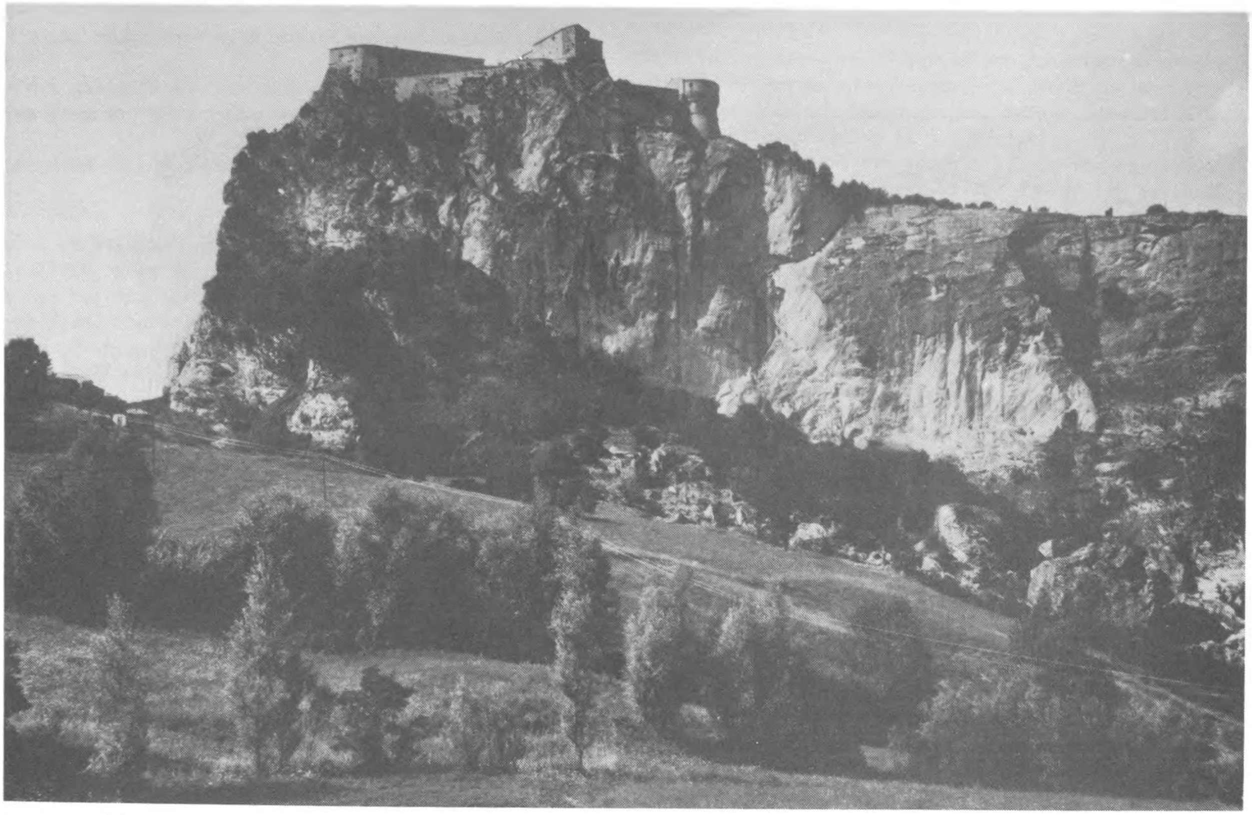


Fig. 2 - S. Leo - A general view of the East side.

The value of the carrying capacity of the anchors was fixed, according to the maximum admissible stress on the rock under the anchor heads. The permanent anchors are of the grouted body under tension type. The corrosion protection consists, in the first work (1969-70) only in cement grout covering at least 2 cm. the bond length, in the following works (1979-80) the protection was assured by a ribbed plastic tube. The chosen methods have given no trouble during the installation and in the following years.

In addition to the normal suitability test, for a number of anchors the test was carried on over a period of 120 days. During the loading and unloading cycles, in order to know the elastic and plastic deformations the maximum load was taken up to a load 1,5 time the working load.

In the area near the town gate, a fall of the 20% of the initial value of the load was noticed. Therefore in this area all the anchorages were again pulled to the foreseen load and tested for another 180 days.

Only after this time, considering that no other loss in tension occured, the free lengths were injected and the anchor heads cemented.

The anchor heads were cemented in niches dug into the rock and sealed with the original rocky fragments, so could be avoided any alteration of the visual approach of the cliff and contemporary obtain the corrosion protection necessary for the heads because of the possibility of hostile liquid agents seeping into the anchor heads.

Considering that the cliff in the recovered area was no more water pervious, a system of microdrains 85 mm. dia, 40÷50 mt. in length was than constructed in order to avoid any danger of overpressures.

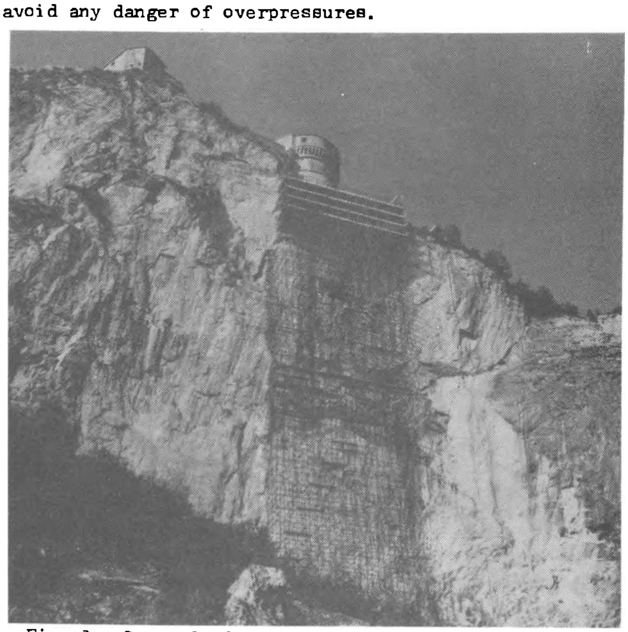


Fig. 3 - General view of the working bridge

O R V I E T O

Geomorphological aspects

The cliff of Orvieto may be simplified considered as a rocky plate formed by pyroclastic deposits of various consistency overlaying the "bed rock" formed by middle pliocenic clays (with a thickness of more than 2000 mt). A layer of alluvial deposits (silty sands and coarsenen gravels) including also some pyroclastic materials, about 10 m in thickness, forms an intermediate element on the stratigraphical series. The shape of the cliff is nearly elliptic, lengthening in the direction E-NE, O-SO, with dimensions roughly 1.600 meters time 850 meters. The walls of the cliff are subvertical and some cases over hanging; their height raises to 50 m. Morphogenetical processes have determined the progressive reduction of the original volcanic "plateau", the separation of the cliff from the surrounding areas and the formation of the valleys, where two small rivers flows, formed in the clay sediment of the bed rock, wheathered by the natural exogenous agents.
The bed rock clays, surrounding the cliff are covered by a thick detrital cover orginated by the progressive erosion of the pyroclastic cliff; the cover contains loose elements and rock fragments, the dimensions of which may arise up to several cubic meters.
In the detrital cover, the thickness of which decrease linear with the distance from the cliff, is located the water table.
Springs appear along the contact with the impervious strata of clay all around the slopes.
The pyroclastic plate, gently dipping N-NE, is clearly layered with giant subhorizontal bedding. We can distinguish always the following levels, more or less altered by diagenesis: hard-tuff, pomiceous tuff marked by stratification planes, hard coherent tuff with black scoria, indurated ashes and very poor cohesive tuff.
The thickness of the various deposits is variable, and the passage from one level to another is continuous without interruption in the stratigraphical series. The bedding is influenced by the paleomorphology.
The tuffs are fractured and their joints are generally closed. In some places the fractures, who run along the whole height of the cliff, are open in the upper part and tend to close coming to the bottom of the cliff. These systems of joints divide the rock into columns and pillars.
The geometrical feature of colummar jointing may be accounted by fracturing by tensional stresses developped due the static fatigue and to the different geomechanics characteristics between the pyroclastic deposits and the underlaying strata.
The number of fracture decrease inside the plate with the distance from the outside boundary of the cliff.

Failures

The general conditions of instability of the tuff cliff and of the underlaying clay slopes are well known and described since the Middle age.
It is interesting to notice that, on the basis of the available historic and iconographic documentations back to 1528 AD, it appears that the areas of the cliff, where the most of the failures occur, are almost always the same. These areas correspond more or less to the sides, where the temperature changes, the meteoric waters and in addition the man's role have been and are more effective.
Failures can be so classified:

- landslides along the slopes (in the pliocenic clays and in the rocky debrise;
- earth flows, mud flows and soil creep;
- landslides in the tuff cliff (along the external boundary of the plate): rockfalls, desquamations;
- local subsidences due undermining inside the town.

The slope of the debrises are at their natural limit and therefore potentially unstable.
Any change in the underground water table, due to unusual rainfalls or to the losses of the hydraulic plants, through the pervious tuff strata of the plate, may trigger a landslide.
Long analysies of the hydrological balance and of the distribution of the pollution along the water wells and the springs laying on the slopes have been carried out in order to evaluate the incidence of the hydric plants losses (acqueduct, sewage plant) in comparison with other causes. The hydric consumption and the corresponding in flow of water on the cliff have increase in the last century from 1 to 4, with a linear connection with the increase in the number and dimensions of the failures.
The meteoric waters are drained by 5 ditches, in which also the sewage waters are carried. The hydraulic capacity of these ditches are now totally insufficient considering the today's water outflow.
Because the natural vegetation has been completely removed, the erosion of the ditches, now perennial, due to sewage plants, allows the formation of local landslides and creeps laterally along the sides and at their head.
The pliocenic clays (bed rock), have been interested during the prehistorical and historical times by many landslides. The structures of the large Etruscan necropoli, founded on the pliocenic clays, that embraces the tuff cliff, originally flat, appear today backtilded and there is between the various burials a differential settlement according to the distance from the cliff.
At the beginning of the century about 2/3 of the North Side collapsed due the undercutting of the clay slope for the construction of the railway Rome-Milan.
The failures, that occur on the walls of the tuff cliff, vary according to the rock conditions from single small fragments to the collapse of a whole front, with no defined slipe plane.
Failures depend on the increase of the tension stresses in the tuff formation due to the greater deformability of the bed rock (clay) in comparison to the pyroclastic deposits, and to the landslides, in the debrises and into the clays, that have reduced or eliminated the retaining forces on the foot of the cliff. The static fatigue, the weathering and the climatic actions have improved the formation of fractures due to the traction in the upper side of cliff. A final but not negligible cause are the waters flowing into the fractures, that may increase, where not sufficiently drained, their hydraulic head therefore improving the hydrostatic pressure on the internal faces of the fracture and triggering the falls

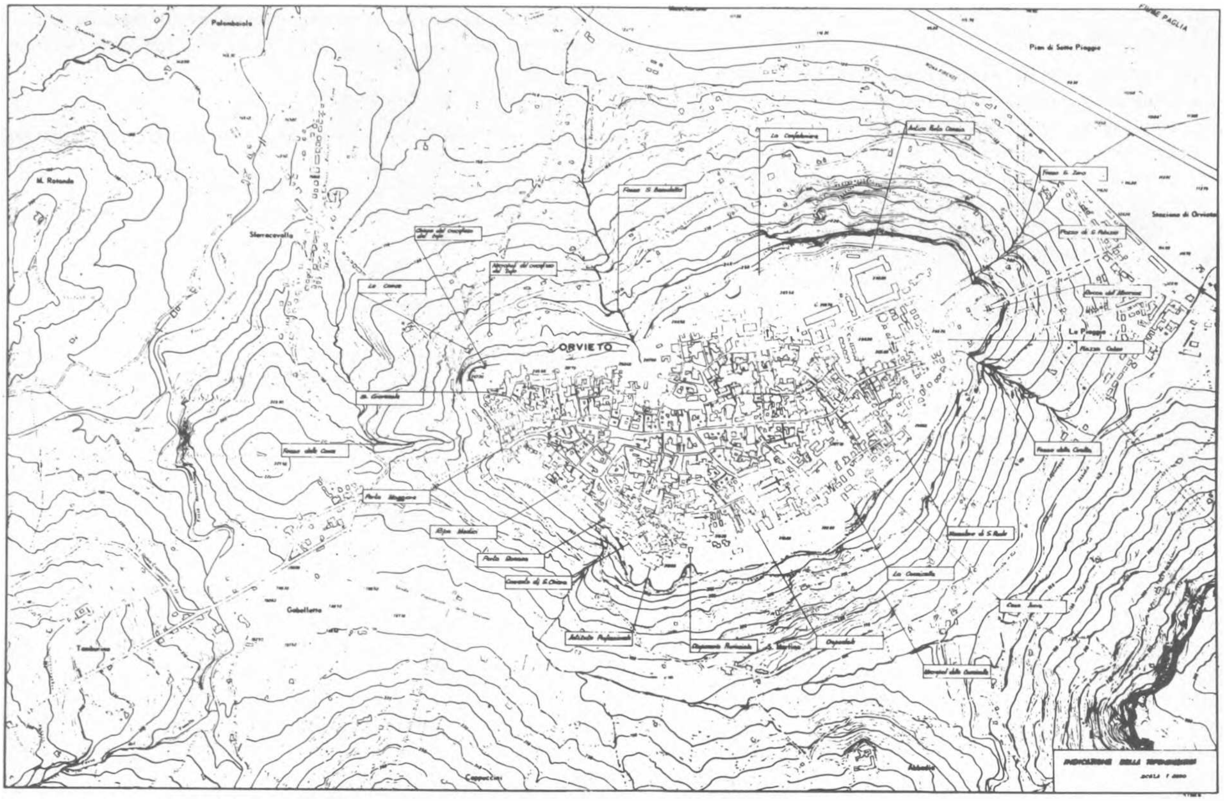


fig. 4 - Orvieto - Map of the site failures occur in the grey areas

of single large rocky fragments or of a whole wall. All these aspects have been investigated with a computer in order to see the mutual interdipendence of the single elements of the problem.

Strengthening and recovery operations

The methods to improve the stability of the cliff regard two different aspects:

- removal or limitation of the causes of the failures,
- reestablishment of the original equilibrium of the hill.

Therefore the foreseen works now starting (1980) aim:

- to limit or eliminate the water circulation inside the tuff plate and the detrital cover (both pervious);
- to avoid the undermine at the bottom of the plate due to possible landslides;
- to reduce the traction stresses, that cause the tension state inside the tuff formation;
- to strengthen the sites, where the failure occured.

The works consist in :

- the general overhauling of both the sewage plant and of the hydric plant, with the construction, where necessary, of new lines;
- the construction of a new system of sewer and water drains to assure proper getting of the meteoric and residual waters along the edge of the cliff;
- the overhauling and the completion of the dams on the radial ditches to assure a proper flow of the waters running now savegely along the slopes;
- the reafforestation all along of the upper edge and the fact of the cliff denudated by the man;
- the drainage of the cliff with a system of subhorizontal microdrains;
- the reestablishment of the original retaining forces at the foot of the cliff, using a net of deep pretensioned anchorages;
- the strengthening and recovering of the site of the cliff, where the failures occured, with anchorages in the upper side of the face of the cliff and with a net of steel cemented nails along the face.

All these works will be controlled with the preliminary installation of a diffuse field instrumentation.

The purpose of the instrumentation, that will be applied both on the cliff and along the slopes, is to study the behaviour of the rock masses, subjected to the consolidation, before, during and after the strengthening operations, in order to see the differences between predicted and actual performances.

The measures, that will be carried on, consist in loading and unloading cycles on the anchorages, in analysing the influence of termic gradient on the rock movements in the cliff, in measuring the pore water pressure and water table changes versus the earth pressure and the movements

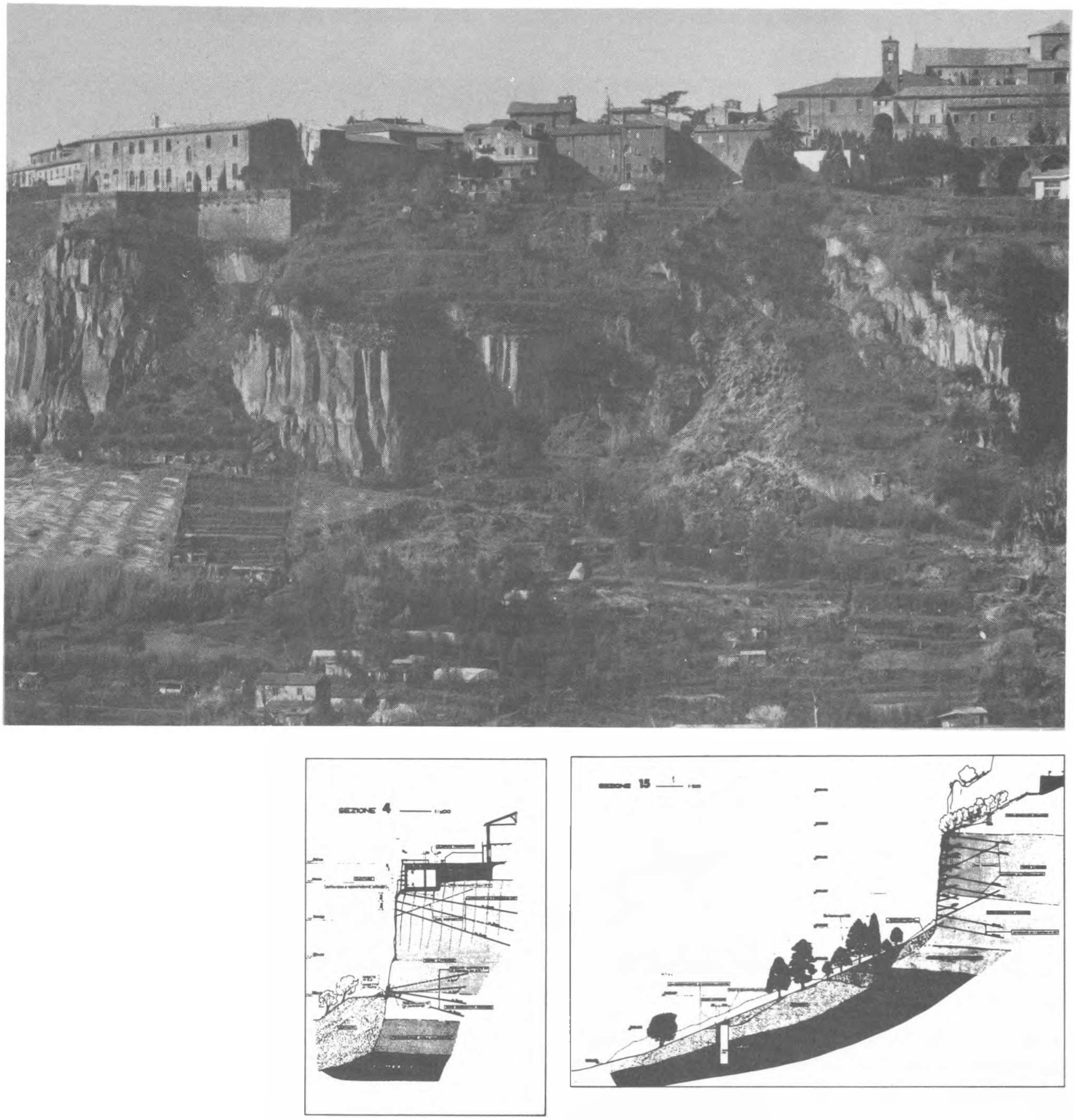
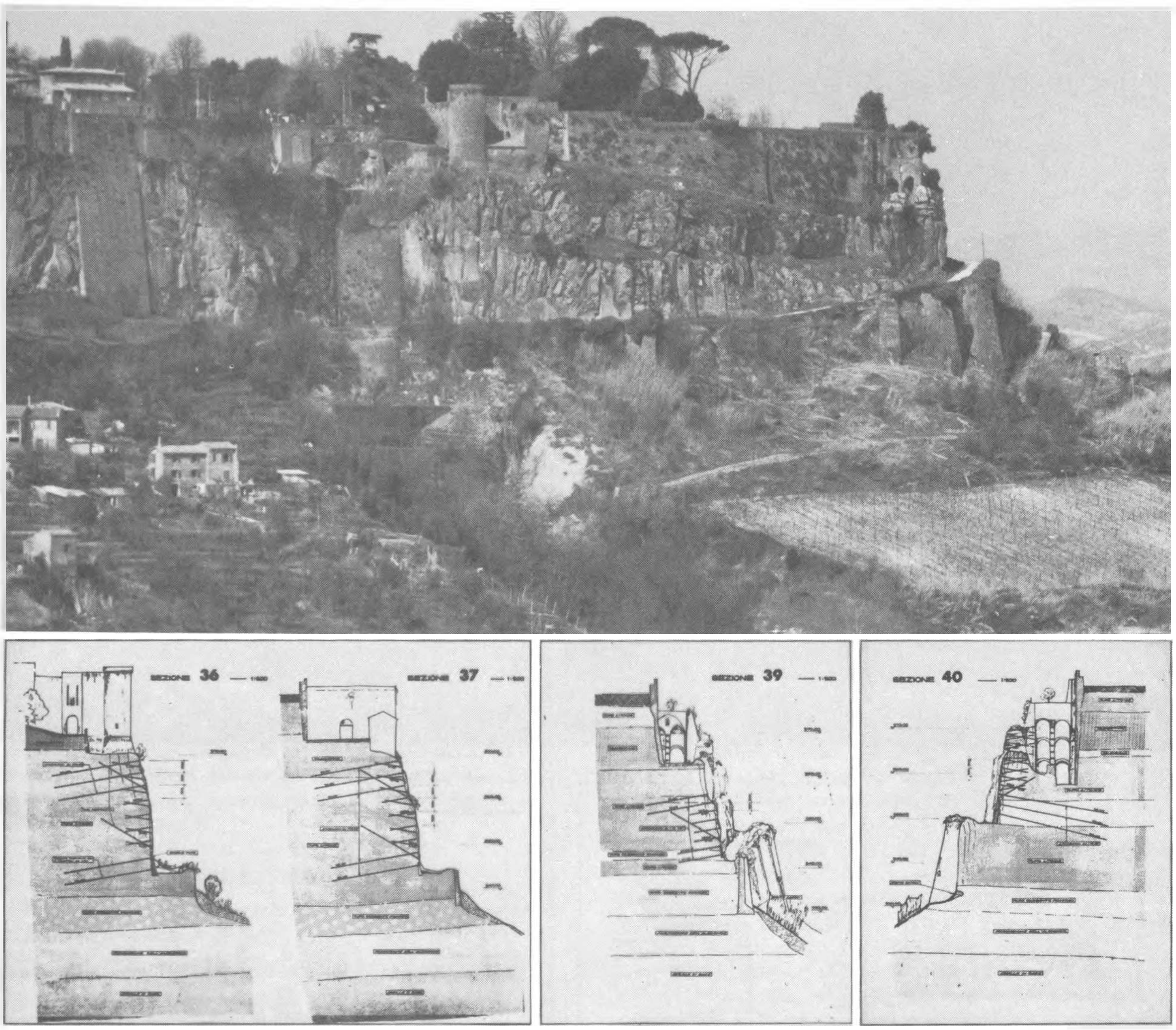


fig. 5 - South side   Failures and Proposed works.



in the slopes.

All the instruments will be fully automatised in order to get continuous results and to avoid any error, in the measures due to the man.

The installations of the retaining and draining structures, are similar to that already executed or in execution in St. Leo and they are described in the enclosed figures for the different sites.

Fig. 6 – The Rocca of Albornoz. General view and proposed works