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The Hill of Todi (Umbria, Central Italy)

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ABSTRACT. The historical town of Todi, in central Italy, lies on the top of a hill made up of clastic sediments in continental facies, typical of a filling stratigraphic series of a Plio-Pleistocene lacustrine basin (Ancient Lake Tiberino). Its particular geologic-lithologic conformation, with basal clays underlying sands and gravels, is responsible for extensive landslides which have threatened the town's stability since historical times. The paper describes the geological, geomorphological and hydrogeological characteristics of the Hill of Todi, the physical-mechanical properties of the basal soils (clays, the main cause of the hydrogeological risk detected) and the types of landslides occurring over time on the hill. The landslide areas are subject to intensive monitoring; here, thanks to the administration of the Region of Umbria, the morphological and hydrological systematization works carried out have made it possible to obtain substantial stability in these areas.

Key terms: Geomorphology, Landslides, Todi, Umbria.

Introduction

The town of Todi, in the Province of Perugia (Umbria, central Italy), stands on the top of a hill (Fig. 1), composed of Quaternary continental clastic sediments, attributable to the Umbrian *Villafranchiano*.

Its propensity to instability, favored by lithological, stratigraphic and structural factors, is similar to that of many other historic towns in central Italy located in "Apennine intermountain basins". These basins are the result of the extensive tectonic stage taking place on the Tyrrhenian side of the Apennine chain in the Plio-Pleistocene, and were gradually filled with clastic sediments in lacustrine and fluvial-lacustrine facies (clays, sands and conglomerates). The basin areas have always been highly populated, also because of important road networks built in the valley, which since ancient times have played an important role in the socioeconomic development of the entire country.

The Hill of Todi, situated at the southwestern edge of one of the largest of these basins (the "Ancient Tiberian Lake", today crossed by the Tiber River – Fig. 2), has suffered many significant landslides over the centuries, distributed almost uniformly over all the slopes, which have in part affected the development of the town.

Fig. 1 – Panoramic view of the Hill of Todi.

The extending of the landslides, which have reached the edge of the historic center and are thus putting the town itself at risk, has led to the passing of a national law (no. 230 of 1978 and subsequent amendments), by which urgent measures have been established for the protection of the town and its cultural heritage (REGIONE DELL'UMBRIA, 1980; 1985; 1988; 1990-91)

A special Technical-Scientific Committee established by the Region of Umbria has carried out an in-depth reexamination of the Hill of Todi's historic proneness to landslides and has reprocessed the control and monitoring data collected until now; during the last ten years it has supervised and directed the works carried out for the stabilization of the slopes and the preservation of the town's historic-artistic heritage.

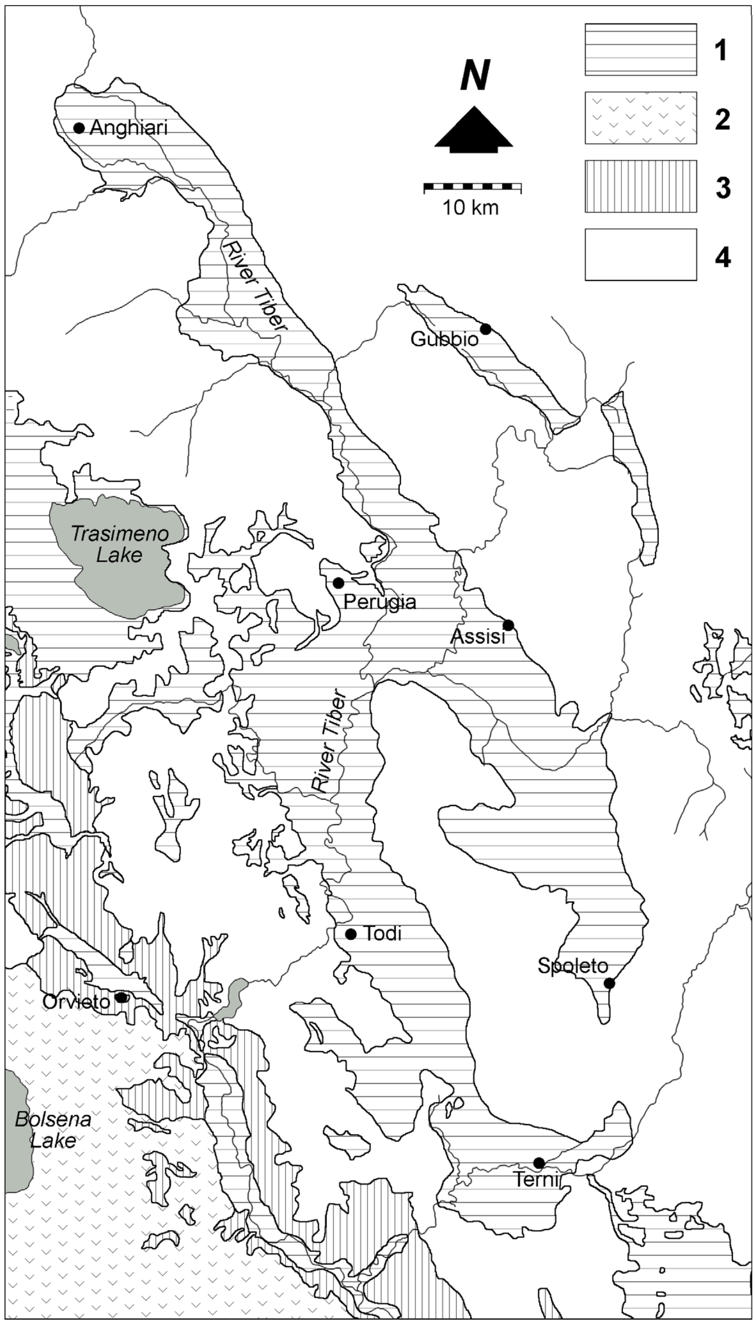

Fig. 2 – Essential geological sketch of the "Ancient Tiberian Lake" area (Umbria, central Italy). LEGENDA: 1) clastic sediments in continental facies (recent alluvial sediments, lacustrine and fluvial-lacustrine sediments, from Pliocene to Olocene); 2) volcanic rocks of the Vulsin Volcanic Complex (Middle Pleistocene); 3) clastic sediments in marine facies (sedimentary cycles of Lower Pleistocene and Pliocene age); 4) pre-pliocenic bedrock.

Geological Description of the hill of Todi

Stratigraphic and structural characteristics

The Hill of Todi is made up of clastic sediments in lacustrine and fluvial-lacustrine facies (from basal clays to conglomerates at the top) deposited at the edges of the ancient basin of the lake known as "Tiberian Lake", the activity of which dates – although in alternate stages – to the Lower Pliocene – Middle Pleistocene (ALBANI, 1962; CONTI & GIROTTI, 1977; AMBROSETTI et al., 1987).

This lake basin, of tectonic origin, was filled with sediments attributable to a regressive-type series, traceable to a stratigraphic system such as that shown in Fig. 3 (BASILICI, 1992).

In particular, the Todi area is situated at the southwestern edge of the basin (see also Fig. 2), where essentially two formations crop out: one deposited on the shoreline, slope and slope-basin of a deep lake (Fosso Bianco Formation - FBF); the other on a humid alluvial fan at the border of the lake system (Ponte Naia Formation – PNF, Fig. 3) .

Most of the Fosso Bianco Formation is made up of marly-silty clays, leaden-colored and full of minute flat-parallel laminations. They are interlayered with sand and sandy gravel bodies that represent slope-apron or shoreface deposits. The slope-apron deposits constitute lithosomes lengthened towards E, surrounded by marly-silty clays of slope or slope-basin sedimentation.

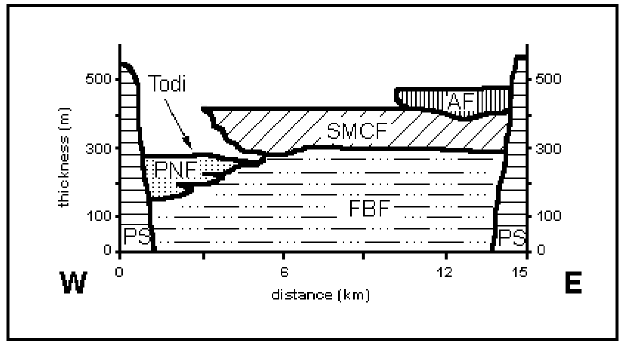

Fig. 3 – Stratigraphic series of "Ancient Tiberian Lake" close to Todi area. LEGENDA: AF = Acquasparta Formation; SMCF = St. Maria of Ciciliano Formation; PNF = Ponte Naia Formation; FBF = Fosso Bianco Unit; PS = Pre-pliocenic Substratum. After BASILICI *et alii* (2000), redrawn.

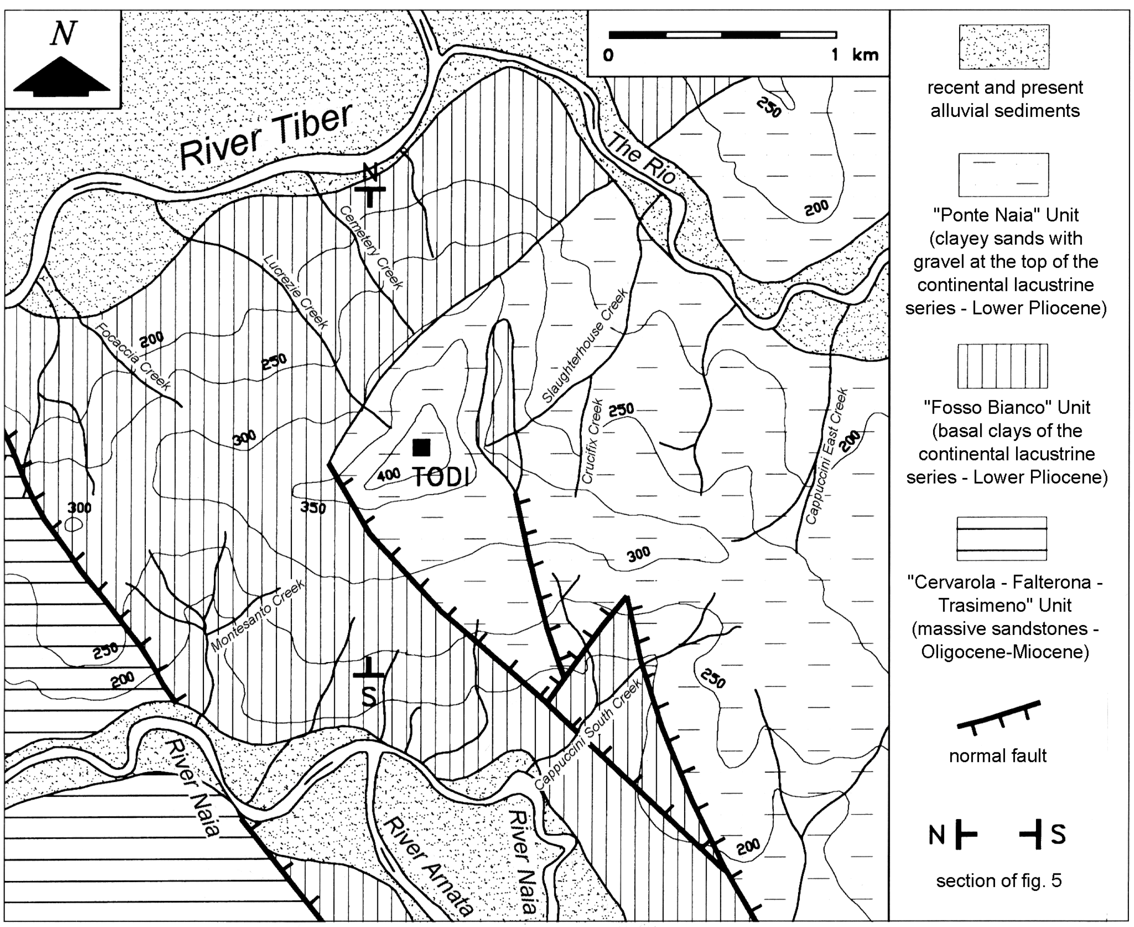

Fig. 4 – Geolithological sketch of the Hill of Todi. After CONVERSINI *et alii* (1995), redrawn.

These deposits are concentrated in the western part of the Hill of Todi, near the pre-Pliocene bedrock. The shoreface deposits have a distribution parallel to the older lacustrine coast (N-S). The contact between the Fosso Bianco Formation and Ponte Naia Formation is not clear, but there is probably a continuity of sedimentation.

The Ponte Naia Formation is made up of deposits formed on a humid alluvial fan, at the margin of the lake system. For the most part the sediment is clayey-sandy silt related to interchannel sheet flow sedimentation. In the lower part of the succession these fine sediments are cut by uncommon sandy gravel ribbon channels. The sedimentary succession of the Ponte Naia Formation shows a change in the architecture moving upward, marked by an increase in size in the sandy gravel channel bodies, as a consequence of the humid alluvial fan progradation (BASILICI et al., 2000).

The basal clays occupy the entire northwestern, western, and southwestern slopes of the Hill, starting from the alluvial plains of the Naia stream and the Tiber River, almost reaching the built-up area of the town, while the sandy-clayey and conglomeratic sediments extend over all of the upper portion of the Hill, including the entire area of the historic center, and part of the eastern slope.

The stratification is sub-horizontal in the deposits at the top of the hill, while the basal clays dip eastward with an angle of inclination of about 10°; thus it is clear that there is a slight angular discordance between the two units. In the lower part of the hill the clays lie in a sub-horizontal bedding or tend to dip very slightly toward the west.

The continental sediments rest, by means of an evident tectonic contact, on the rocky pre-Pliocene substratum of the "Cervarola-Falterona-Trasimeno" tectonic Unit, composed of massive sandstones overlying the "Scisti Varicolori Auctorum" Unit. The contact is visible in the Pontecuti area at the foot of the hill, and is marked by a normal fault sharply dipping NE (Fig. 4). Another fault, with a not clearly definable throw, parallel to the preceding fault, is found in the Fornace Toppetti area. These are associated with a system of jointing with a roughly NE-SW direction, very evident within the basal clays in the area of the Lucrezie gully, which drains the northwestern slope of the hill (CONVERSINI et al., 1995).

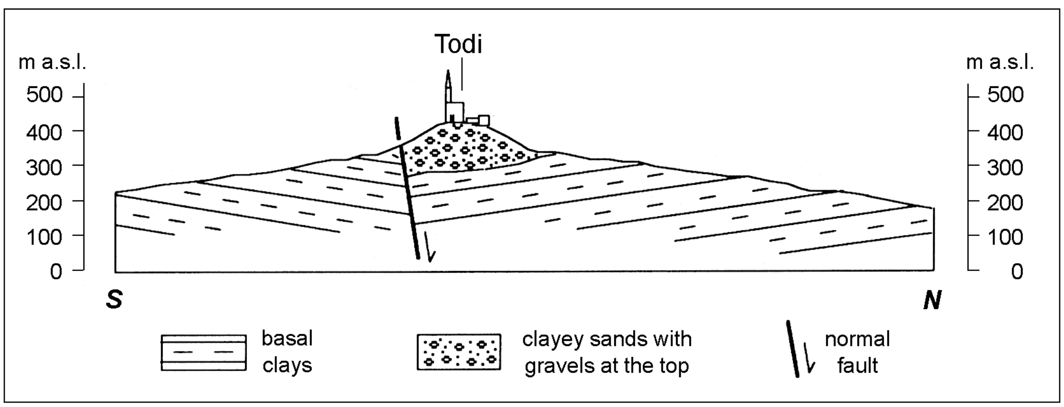

Fig. 5 – Schematic geological section through the Hill of Todi. After CONVERSINI *et alii* (1995), redrawn.

Geomorphologic Characteristics

The hill upon which the town of Todi is built has modest slopes at the foot (10-15%) which become steeper (up to 40-45%) at the top. It is evident from this that the rock types near the top (conglomerates and sands) are more resistant to erosion than are the basal clays. As a consequence of the alternating of rock types with different erodibilities, there are frequent abrupt changes in slope, especially on the eastern side, with the formation of selective erosion scarps at various heights, where the conglomerates come into contact with the softer rock types having a higher clay content.

On the northwestern side the original morphological configuration evolved rapidly, due also to the undermining action of the Tiber River, which produced more or less evident bights along the foot of the hill, triggering large landslides. The western and southwestern sides of the hill, instead, are those with the gentlest slopes (averaging about 10%), due to the outcropping up to greater heights of clayey rock types with weaker mechanical properties (CONVERSINI et al., 1995).

The entire hill is drained by a series of gullies, with centrifugal drainage, characterized by strong erosion processes. These cut into the deposits at depths of up to 7-8 meters lower than the surrounding ground level, favoring gravitational processes in the slopes. Their flow discharges are extremely variable during the year; until the stabilization works were carried out, the flows were also influenced by the amount of drainage from the town sewer system, which drained mainly into the Mattatoio, Lucrezie and Cimitero gullies. All of these gullies flow into the three main watercourses at the foot of the hill (the Tiber River, and its two most important tributaries in the area, the Il Rio and Naia streams). Fig. 6 shows a geomorphologic diagram of the Hill of Todi.

Hydrogeological Characteristics

The heterogeneity of the soils forming the Hill of Todi has a strong influence on the degree of permeability of the deposits, creating hydrogeological conditions that are complex, variable, and difficult to predict (COLUZZI et al., 1995). On the whole, it can be said that the primary-type permeability of the deposits decreases with depth, going from the sandy-conglomeratic complex to the mainly clayey base complex. There are considerable local differences from this overall situation, however, related both to the deposit heterogeneity and to reworking phenomena ascribable to gravitational ones. Probable tectonic disturbances inside the hill complicate this general model of the circulation of groundwater, favoring the possible presence of deep drainage lines.

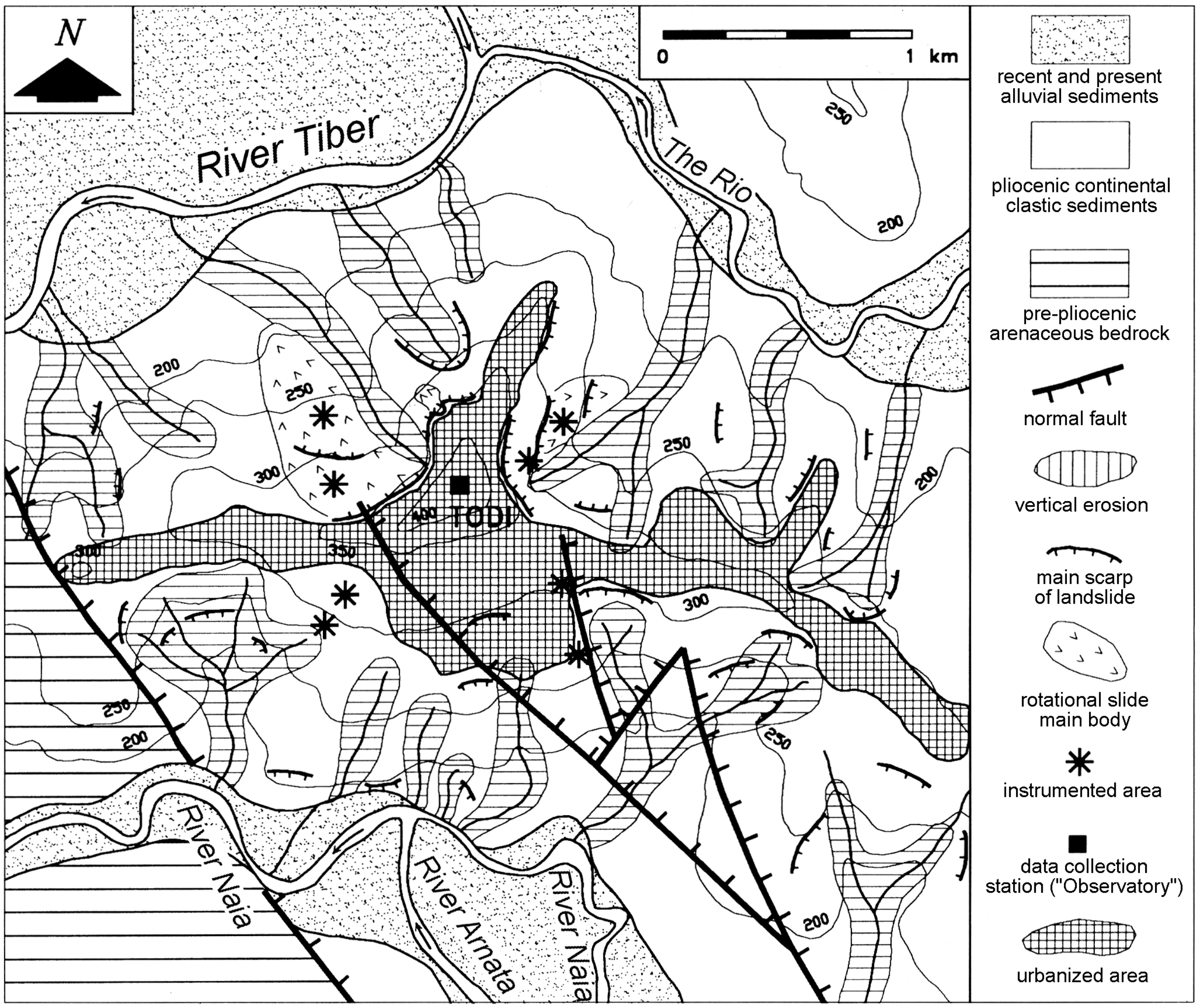

Fig. 6 – Geomorphological sketch of the Hill of Todi. After CONVERSINI *et alii* (1995), redrawn.

The presence of water-bearing strata perched over the basal stratum is nonetheless documented by the existence of numerous wells (once exploited for domestic use and today mostly abandoned) that despite their relatively shallow depth (5-6 meters) had flows that reached up to a few liters per minute.

During a study of the stability of the Hill made in 1969 (PIALLI & SABATINI, 1969), 355 wells and cisterns of various depths and from different periods were counted in the historic center area alone. Hydrogeological monitoring was carried out on over 100 of these, through both the measurement of the piezometric level and the chemical-physical analysis of the groundwater. A hydrogeological map was proposed in the same work, with the trend of the isophreatic contours in the upper urbanized part of the hill, which showed two lines of preferential underground drainage flow, coinciding on the surface with the Lucrezie gully on the eastern side and the Mattatoio gully on the western side. This was confirmed in a later study (DRAGONI, 1979), based essentially on the measurement of some parameters of water pollution at various points where it issues along the slopes of the hill.

As part of the activities of the regional Technical-Scientific Committee, during the 1998-99 period greater knowledge was obtained on the hill's hydrogeological characteristics through the periodic measurement of the piezometric level in the wells present in the slopes and through the chemical-physical, isotropic and flow analyses in the two springs in the town (known as the "Fonte Etrusca" and the "Fonte Scarnabecco"). These are two drainage tunnels that tap the small aquifers in the upper sandy-conglomeratic deposit and whose waters were collected in a system of tanks for domestic use.

Although both of these springs are characterized by a perennial regimen, they have modest flows, in the order of a few liters per minute. The water temperature during the period of observation oscillated according to seasonal temperature changes; this denotes the superficiality of the aquifers, which are subject to rapid recharge.

The chemical composition is typical of bicarbonate-calcium-containing waters, while in two measurements made in 1998 and 1999 the isotopic content proved very homogenous, with values respectively between –6.32 and -6.44 for $\delta^{18}O$ and -40.6 and -41.1 for $\delta^{+3}H$ (values totally compatible with the isotopic composition of the meteoric water in the areas of western Umbria). Thus it can be excluded that there are external sources other than those of the simple surface infiltration waters, with seasonal recharge.

Mechanical characteristics of the soils

The evaluation of the physical-mechanical characteristics was limited to the gray-blue basal clays. Three study campaigns were conducted by the Region of Umbria: in the 1976-78 period, in 1989 and in 1991 (REGIONE DELL'UMBRIA, 1990-91). Although the sampling took place over very vast areas, the materials showed great homogeneity in their index properties. The clay can be classified as *"inorganic clay of medium plasticity and low activity,"* with a plasticity index of 25% and a volume unit weight of about 21 kN/m^3. The mechanical tests carried out *in situ* and in the laboratory showed evidence of strong surface alteration phenomena. The alteration band thickness averaged 5-6 meters, but may be greater locally.

The non-drained shear strength (c_u), measured using TXUU tests, varied from 50 to 70 kPa in the altered layer, and reached values of up to 500-600 kPa at depths of around 20 m below the ground level. The drained shear strength, measured from direct shear tests, was quite variable, as regards both peak values and, to a lesser degree, residual values. A simple statistical average of the results in peak conditions gives c' = 25 kPa, φ' = 28°; in residual conditions we have: c' = 7 kPa, φ' = 19° (CONVERSINI et al., 1995).

Landslide Phenomena

Ancient Landslides

The Etruscans, after having built the circuit of defensive walls, constructed drainage works just outside the town, an evident sign that since those times there has been the need to carry away rainwater because of the landslide problems that they were able to cause. There are reports of a large earthquake that struck Todi in 303 AD; the fact that the seismic catalogs make absolutely no mention of any earthquakes in that year leads one to believe that instead it might have been a large landslide, with surface effects interpreted as an "earthquake" by the inhabitants.

An important research on the historical landslides of the Hill of Todi was conducted recently by the ENEA (Environmental Department) and published in collaboration with the Region of Umbria (MARTINI & MARGOTTINI, 2000). The research covers the period from 1150 to 1991 and reports the documenting of 223 landslides, 148 of which taking place after 1800. The greater frequency of events reported in the last century is surely related to the scarcity and incompleteness of less recent historical data. The first document with reliable reports of landslides is from 1150 and describes a landslide occurring along the northwestern side of the hill, between the Lucrezie and Cimitero gullies, notoriously one of the areas that later proved to be among those most subject to landslides (BIONDI & MENOTTI, 1977; TONNETTI, 1978; CALABRESI et al., 1980). Other documents that explicitly mention landslides go back to 1351, the year in which it was prohibited to cultivate the land in some areas surrounding the city walls (COLUZZI et al., 1995).

Numerous landslide phenomena occurred in the following centuries, until significant collapses in the city walls took place in 1750, and in 1794 the Ospedale della Carità (Charity Hospital) was declared unfit for habitation and abandoned. Following the Unification of Italy, in 1865 the Municipal Council asked the central government for funds, in order to remedy the main landslide situations existing along the slopes of the hill. In the early 20th century, Viceregal Decree no. 299 of 2 March 1916 declared that the town of Todi required "consolidation."

More recent landslides include that of 1941, which caused the collapse of the central arcades of the public gardens, and in 1965, the collapse of a reinforcement wall for the street running alongside the gardens. After this came a viaduct built on pilings, the central piers of which shifted downhill in 1969. In 1971 they were definitively stabilized with the constructing of large diameter piles, driven to a depth of 40 meters below the ground level.

The location of the landslides reported in the summary by MARTINI & MARGOTTINI (2000) points out an interesting fact, i.e. that the majority of the landslides were localized in the catchment basins of the Lucrezie and Mattatoio gullies, and mainly at the head of the two watercourses. Other landslides are distributed rather evenly along all the slopes of the hill.

This distribution suggests that there is a relation between landslides and the geometry of the phreatic stratum, shown by the trend of the isophreatic contours in the work by PIALLI & SABATINI (1969) cited earlier. In fact, the hydrogeological map included with the work of those two Authors shows a concentration of underground drainage running in the same direction as the two gullies mentioned: the meteoric infiltration water thus appears to have two preferential underground flow directions. This seems to be confirmed also by the presence of the only two historic "springs" in the town of Todi, the "Fonte Scarnabecco" and the "Fonte Etrusca," right at the head of the two gullies.

Landslide types and characteristics

The majority of the landslides occurring on the Hill of Todi can be classified as "slides" and "flows" (WP/WLI, 1993), which occur along well-defined failure surfaces or, at times, within a more or less thick band of clastic material. Two main types of movements can be identified: 1) landslides moving parallel to the slope, involving exclusively colluvial material; often in this case the landslides can be interpreted as simple solifluction or, at the most, flow phenomena involving a thickness of materials not greater than 5-6 meters; 2) prevalently rotational slides, when the failure mechanisms involve also the clastic Pleistocene-Quaternary sediments. These movements, which are larger and deeper, are those that occur, for example, in the Lucrezie, Cimitero and Mattatoio gullies (DRAGONI, 1979; CALABRESI et al., 1980; CALABRESI & SCARPELLI, 1984a, 1984b; COLUZZI et al., 1995; MARGOTTINI & MARTINI, 2000).

As regards the more superficial landslides, belonging to the first of the two types described, it can be said that the scarcity of wooded areas and the uncontrolled flows of surface water, together with the tendency toward vertical erosion of the watercourses flowing down the hill slopes, may be considered the main predisposing factors for this type of landslide. In the past, the mechanical deep plowing for cultivation at the foot of the city walls also contributed, often decisively, to the general deterioration of the mechanical properties of the soils (COLUZZI et al., 1995). The increase in interstitial pressures taking place during abundant rainfalls is normally the true "cause" of the landslides, understood as the "triggering factor" of the movement.

The landslides of greatest proportions, which involved materials from the upper conglomeratic complex as well, just outside the built-up area of the town, were the most serious and important phenomena with regard to the stability and safety of the town, and most studies have been concentrated on these, for preventing and mitigating landslides risks.

It is clear how the hydrogeological characteristics of the upper complex, which is very permeable and subject also to leakages in the town water mains and sewer systems, have been a decisive factor in these types of landslides. In the past, before the works for controlling water flows and the rebuilding of the entire water distribution and sewer networks were carried out, these leakages played a crucial role in causing the deterioration of the mechanical properties of the soils and, therefore, the triggering of the largest landslides, in which the rotational component of the movement was preponderant over the translative one.

The areas where the largest landslides occur were the topic of stability analyses which provided shear strength parameters close to the residual parameters measured in the laboratory (see the *Mechanical characteristics of the soils* chapter).

Stabilization Works on the Hill of Todi

Briefly, the works proposed, and for the most part already completed (following the passing of the aforementioned laws, which made it possible to obtain the necessary funding, though in several stages), may be described as follows (CONVERSINI et al., 1995):

- complete rebuilding of the entire the water supply and sewer networks in the historic center and urbanized areas along the slopes;
- clearing out, enlarging and repairing of the drainage tunnels built underneath Todi in various historical periods;
- impermeabilization and repaving of most of the streets and squares in the historic center;
- specific interventions aimed at restoring the stability of some works (construction of underpinnings, reinforcement works and anchorings);
- works on the gullies, aimed at containing vertical erosion and bank erosion, one of the main causes of slope landslides. The work consisted of the building of dykes, containment works, and surface drainage works (Fig. 7);
- work on the land along the slopes, including the building of retaining and reinforced earth walls, the controlling of surface water flows and the reconverting of agricultural methods, with the limiting of deep plowing;
- hydrogeological works, aimed at lowering the potentiometric surface of the water tables closest to the surface that affect the colluvial material, and at preventing this water from reaching the underlying sediments with a higher clay content. These works consisted of the building of drainage ditches (3 to 8 meters deep, depending on the thickness of the colluvium) made from inert materials and lined with geotextile fabric;
- other hydrogeological works, aimed at the drainage of the deeper aquifers. Thus in the areas of greatest interest (such as that in the Cerquette area, located near the head of the Lucrezie gully), drainage systems were built that were composed of wide-diameter, 30-meter deep drainage wells equipped with an external "crown" of drilled piles, also having a large diameter (∅ = 1-1.2 m). The wells midway down and near the foot were made to a depth of about 20 meters and were filled with draining materials. All wells

were provided with a splay of subhorizontal drains, with an average length of 40-50 meters, on two or even three levels. The wells were provided with connection structures for allowing the definitive drainage of the water by gravity (Fig. 8).

Fig. 7 – Detail of the hydraulic works carried out along the Cemetery Creek (from COLUZZI *et alii*, 1995).

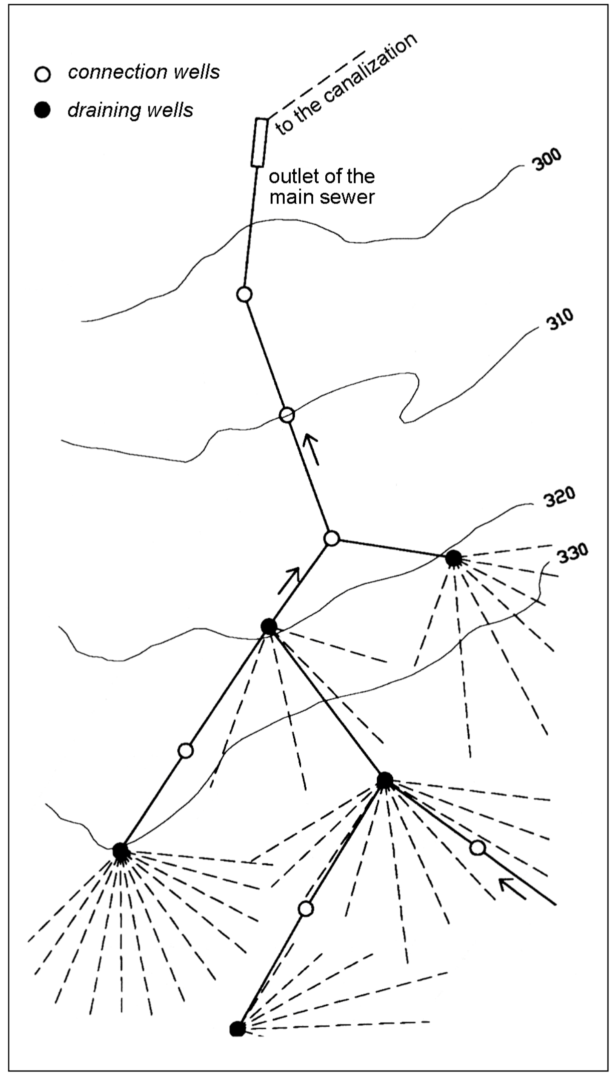

Fig. 8 – Schematic plain of the drainage wells, Cerquette area (Lucrezie Creek). After CONVERSINI *et alii* (1995), redrawn.

Monitoring of the works carried out

Monitoring and surveillance systems were set up for the analysis and monitoring of the stabilization works carried out and being completed (Fig. 6). A meteorological data station and 35 piezometers (26 open tube and 9 Casagrande-type), located along the slopes of the hill and considered strategic for the monitoring of landslide movements, make it possible to measure the level of the potentiometric surface and to discover the relationships between the groundwater regimen and the precipitation regimen. In some cases the piezometers are equipped with electric sensors, providing a centralized, combination manual/automatic monitoring system. Along with the piezometers, 18 inclinometric tubes were installed, equipped with a data acquisition system that is also part manual and part automatic.

The installing of deformation bars and temperature sensors, as well as the periodic monitoring of the tension of anchorage tie rods, was also provided for at reinforcement

anchorage tie rods, was also provided for at reinforcement and retaining structures (e.g. on the piers of the public gardens viaduct). The entire system is completed by a series of topographic (plano-altimetric) control points for the slopes of the hill, the most important structures and the main support works, for which both traditional and GPS measurements are used.

The whole of the works done and those being completed require adequate monitoring and maintenance. With this end in view, a "Permanent Observatory for the Monitoring and Maintenance of the Hill of Todi" was created (as had already been done for Orvieto), the activities of which are aimed at managing the collecting and processing of data deriving from the network of instruments, carrying out the routine and special maintenance on the works done, and the studying, documenting and publishing of the results obtained, also as a reference for similar situations in other unstable towns throughout the entire country.

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