Associazione Geotecnica Italiana

INTERNATIONAL WORKSHOP

OCCURRENCE AND MECHANISMS OF FLOW-LIKE LANDSLIDES IN NATURAL SLOPES AND EARTHFILLS

Sorrento, May 14-16, 2003

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EDITOR

Pàtron editore
BOLOGNA

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40050 Quarto Inferiore (BO)
Tel. 051.767003
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E-mail: info@patroneditore.com
Sito: www.patroneditore.com

Published by Pàtron Editore
Via Badini, 12 - 40050 Quarto Inferiore - Bologna

TWO CASES OF MUDSLIDES IN DIFFERENT GEOLOGICAL AND CLIMATIC ENVIRONMENTS

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ABSTRACT: The research deals with the evolution of instability phenomena and examines the causes of the reactivation of two mudslides occurring under different environmental conditions. The first mudslide affects the village of Sant'Agata Feltria (Central Italy), whereas the second occurs in an area very close to the famous town of Cortina d'Ampezzo (North Italy). The mechanisms that govern the two landslides are quite different due to the different extent of the landslide catchments. The long-term monitoring carried out for years in both mudslides allowed to define the hydrogeological and kinematical features in the landslide bodies. The paper provides results useful to understand the mechanisms at work and plan the most effective mitigation works.

Keywords: Mudslides, Modelling, Monitoring.

1 INTRODUCTION

Both the cases of mudslides presented in this paper affect inhabited areas.

The mudslide of Sant'Agata Feltria has a long history of damage induced by the large landslide movement in the past centuries. The records of the past events are well documented at least since the XVI century, in relation with the "Little Ice Age", until nowadays. The last damaging and harmful event occurred in spring of 1934, after 8 months of exceptional rainfall and a particularly mild winter, without a frozen surface and a snow covers on the uphill sandstone plateau which works as a huge natural tank for the landslide. After this date the landslide continued moving slowly for years, as shown by aerial photos taken during the following 20 years.

The study started with the aim of preventing the village from the most severe consequences following recurrent climatic fluctuations capable to remobilise the large landslide to the maximum extent (maximum length of 5.4 km). A comprehensive monitoring system was installed and carefully checked. At the present time drainage mitigation works, are going to be built up.

The mudslide of Alverà has not a very long history of records, but at least since 1879 there were several records witnessing repeated movements. In the early '70, after the construction of some new houses at the toe of the mudslide, clear evidence of structural damage revealed itself.

Only in the early '90 the Veneto Region set up some site investigations. In 1989 the National Research Council, within the framework of a more extensive research started to install a sophisticated monitoring system.

Thanks to this automatic monitoring system, several significant time-dependant data were obtained; all the temporal changes of the parameters governing the landslide mechanism were observed and used for simulation and diagnostic numerical modelling (Angeli et al. 1996b).

In relation with the different regime of the groundwater supply the two mudslides studied show a slightly different mechanism, the first moving due to the overcoming of the undrained coesion whereas the second due to the rising of the water table.

2 CASE HISTORIES

The village of Sant'Agata Feltria is located in the north-western end of the Marche region, at the boundary with the Romagna region (Fig. 1); the territory is typically hilly, with altitudes ranging between 265 m asl and 930 m asl.

The landslide affecting the village of Sant'Agata Feltria (Fig. 1) is very ancient and its reactivation has been recorded at least twelve times starting from the XVI century. It presents itself in the form of a mudslide 5.4 km long, which crosses the inhabited area endangering many buildings and roads. The last important landslide event occurred at the end of the winter of 1934, after a very critical rainfall season. Major damage to the buildings and to the infrastructure induced the Central Government to require the Air Force to make investigations with the most sophisticated instrumentation available at that time. Aerial photos were taken just after the event (Fig. 1) in order to record the size and the shape of the landslide. Thanks to these photos we are now able to assess with no doubt the maximum extent of a new possible event.

The main mass movement involves part of the village of Sant'Agata Feltria, dividing it into two parts, as clearly shown by the damage to the buildings during the critical event of March 1934 (Fig.2). The mass movement is 5.4 km long and has about 665 m of vertical descent (from about 930 m asl down to 265 m asl), with an average slope angle of about 12°. It is up to 1.6 km wide and involves more than 50 million cubic metres of terrain. For its large size and for having hit the village many times in the past, this phenomenon has been the object of detailed investigations, especially after the strong earthquake of 1997.

Historical research, geomorphological analysis and geotechnical investigations allowed a detailed reconstruction of the evolution and the mechanism of the phenomenon.

The first documented activity period dates back to 1561, when the movement had already assumed its present shape and direction, even though a notary act dated 1485 reports about a "ruined area" in the surroundings of the castle. It must be taken into account that the second half of the XVI century was characterised by very severe climatic conditions, with the deposition of a thick snow cover and intense rainfall, coinciding with a colder phase of the "Little Ice Age". The second documented activity period occurred in 1604, again characterised by a particularly severe climate.

The recording of particularly late dates for the starting period of vintages have been used to recognise unusual and severe climatic conditions.

Further movements occurred during 1644 and 1647, when the climate, even though progressively getting better, was still characterised by intense precipitation. During the second half of the XVII century climate conditions improved and consequently no landslides have been documented in the area.

Starting from the beginning of the XVIII century, the climate turned cold and humid, as testified by many documents related to soil instability. In particular, in 1714, 1723, 1743, 1748, 1750, 1753, 1754, 1756, 1758, 1772, 1773 and 1781 indications of landslide activity have been found.

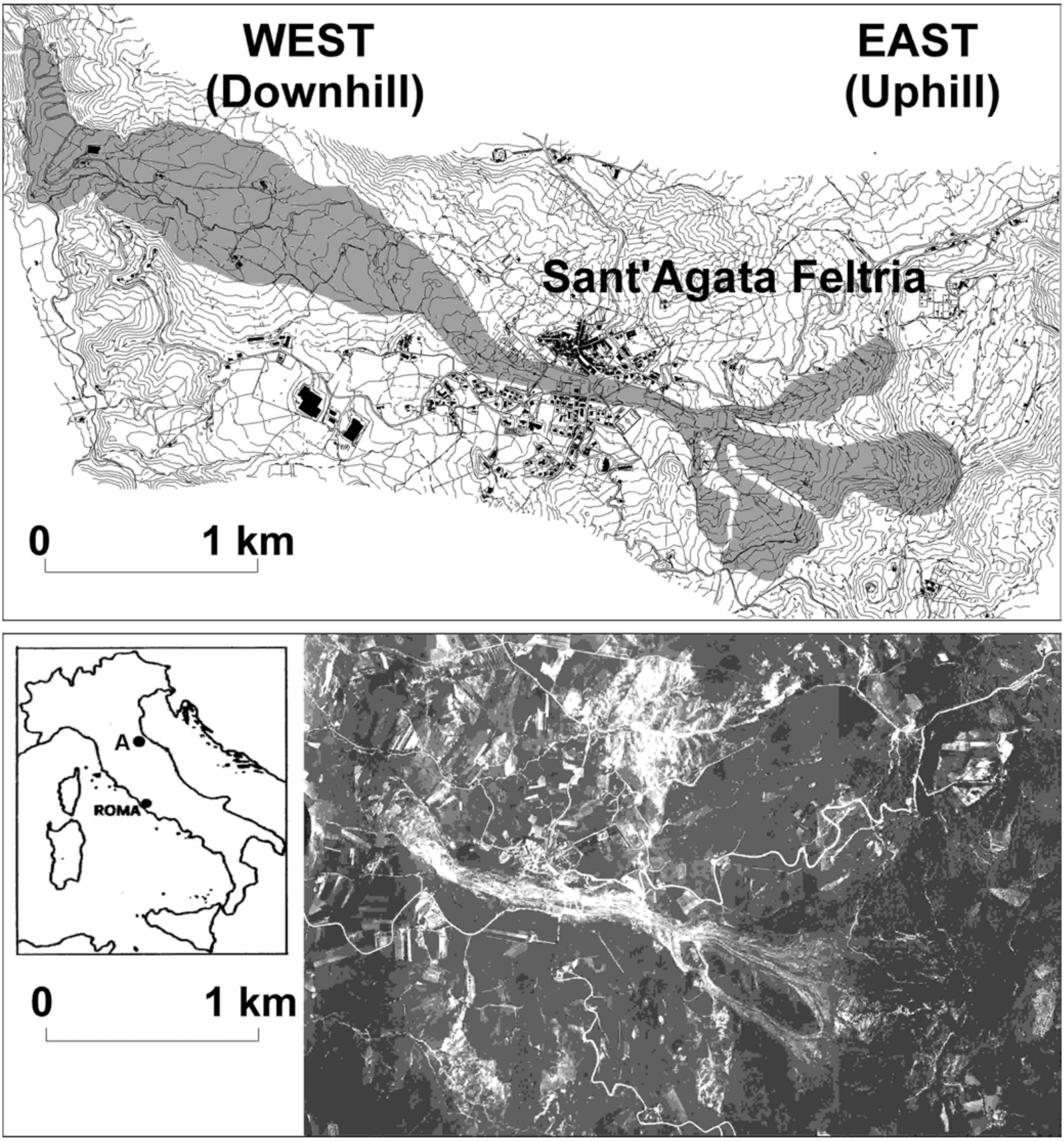

Figure 1. Landslide map and aerial photo of the event that occurred in March 1934 (at that time the remobilisation of the mass stopped just 1 km downhill the village) with a location map of the village (A).

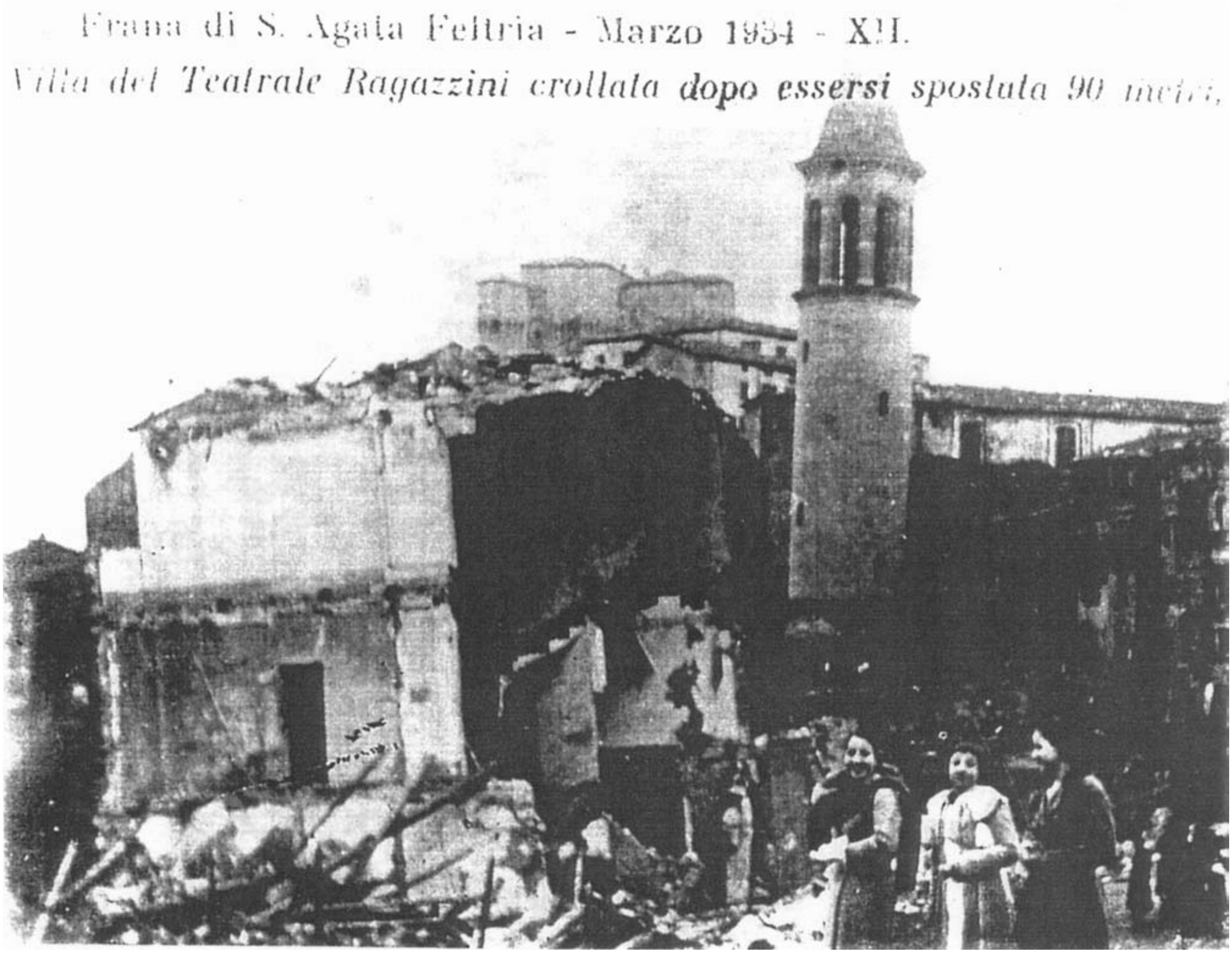

Figure 2. Damage to the buildings during the critical landslide event of March 1934.

In 1782, a strong earthquake affected the area damaging some buildings, but no report exists of remobilization of the landslide.

Then the landslide reactivated during the winter 1801-1802 and in 1803. In 1815 a partial remobilization took place. Successive events of remobilization happened in 1834, 1839, 1840,1844, 1845 and 1846. Starting from 1848 the climate iproved again, and, therefore, for several years no landslides took place.

In March 1934, after a prolonged and severe rainfall period, the mudslide experienced a strong reactivation.

The geology is characterised by terrains belonging to the Val Marecchia complex and the Umbria-Marche Sequence out crops (Angeli et al. 1996a).

The chaotic complex of the Val Marecchia (emplaced by gravity during the lower Pliocene) is made up of allochthonous Palaeogene scaly multicoloured clays (Liguridi) with Oligocene sandstones and pelitic sandstones of the Monte Senario Formation (Epiliguridi).

The Umbria-Marche succession in this area is represented by Messinian units underlying the Val Marecchia complex. The Messinian units are formed by interbedded sandstones and marly clays (Marnoso-Arenacea and Ghioli di Letto Formation) and by microcrystalline gypsum with intercalated bi tuminous clays and solphide-bearing dolomitic limestones (Gessoso-Solfifera Formation).

Some geotechnical results of laboratory tests carried out on several samples are listed in Table 1. Cortina d'Ampezzo is situated at the bottom of a large valley, crossed by three main watercourses: River Boite, Bigontina and Costeana torrents (Fig. 3). This valley is part of the eastern Dolomites (north-eastern Italy).

The mudslide, affecting the villages of Staulin and Alverà, is located in the mid-area of confluence of the River Boite and Torrent Bigontina, 1 km to the east of Cortina d'Ampezzo town and it develops from an altitude of about 1700 down to 1300 m asl. The length of the movement is about one kilometre and the area affected is about 40 hectares.

Table 1. Sant'Agata Feltria mudslide: geothecnical characteristics of the materials

Samples location	CF (%)	W_l (%)	I_p (%)	γ_{sat} (kN/m3)	ϕ_r (degree)
Any depth in the slope	23.50-44	37-75	14-38	14.24-21.47.	13.80-24.51
Slip surface	45-48	55-61	28-35	19.31-20.59	9.14-11.42

Figure 3. The Alverà landslide and the villages of Staulin and Alverà.

In 1935 the villages of Staulin and Alverà were included in the list of the towns to be relocated at the expense of the Italian government; since 1879 there are several records witnessing repeated movements of the Alverà landslide, and works carried out. The most dangerous reactivations occurred in 1979, 1924, 1927, 1935 and 1942 when some private houses had to be evacuated; further reactivations took place in 1966 in connection with the ruinous flood which affected north eastern Italy. In 1986 the Regional Office of Civil Engineers of Veneto carried out control works consisting of a network of drainage surface channels and gabions to protect some buildings. In addition boreholes were drilled for a series of geognostic tests and several topographic bench marks were located (Fig. 4).

The mudslide takes place for its overall extent in the clays resulting from the weathering processes affecting the S. Cassiano Formation. A sample of peat collected at the slip surface was dated back to 8,710±70 yr B.P. (Gasparetto et al. 1994).

The stratigraphical sequence cropping out in the area of Cortina d'Ampezzo covers a period of time spanning from the Ladinian to the Lias.

- S. Cassiano Formation (Upper Ladinian - Upper Carnian). It prevalently consists of marls and shales from basin deposits, intercalated with grey coloured biocalcarenites. Its total thickness in the Cortina d'Ampezzo area is up to 350 m.

- Dolomia Cassiana (Lower - Upper Carnian). It is made up of white greyish crystalline dolomites, which are generally massive; it gives rise to impressive rock walls. The thickness is about 400 m.

- Dürrenstein Formation (Upper Carnian). It consists of peritidal terrigenous-carbonate shelf deposits. The thickness is 100 to 250 m.

Raibl Formation (Upper Carnian). It is made up of polychromic pelites and marls, afanitic limestones and microcrystalline dolomites which, owing to their intense colour and high erodibility, produce evident morphological discontinuities which separate the Dürrenstein Dolomite from the Dolomia Principale. The thickness is about 100 m.

- Dolomia Principale (Upper Carnian - Norian). This formation is widely exposed in the area of Cortina d'Ampezzo, making up the main mountain groups. It consists of white and grey cyclic dolomites, in which stromatolithic and massive lithozones are present. In the area investigated the thickness of the formation is up to 1000 m.

- Dachstein Formation and Calcari Grigi (Rhaethian - Lias). These formations outcrop in the peak of Tofane and Mt. Sorapis and consist of bedded light grey micrite, bioclastic and oolitic limestones, widely affected by karst phenomena, both superficially and at depth. They reach a thickness of about 600 m.

From the climatic point of view the Cortina d'Ampezzo area is quite varied because of its wide altitude range. The climate of the area may be defined as Alpine type, from cold to temperate, with variably cold winters and mild summers. The pluviometric regime reflects the typical Alpine climate pattern. Late spring and summer are the most rainy periods, with a peak in July. In this case, rainfall occurs mostly during violent storms, with intense and concentrated precipitations. A secondary maximum is recorded in November, following the prolonged autumn rains. In regards to snowfall, the period of permanent or almost permanent snow normally begins in December and lasts until April. In the higher areas this period usually lasts for a couple of months longer. The thickness of the snow cover is on average 50 to 100 cm. The average yearly temperature is around 6 °C.

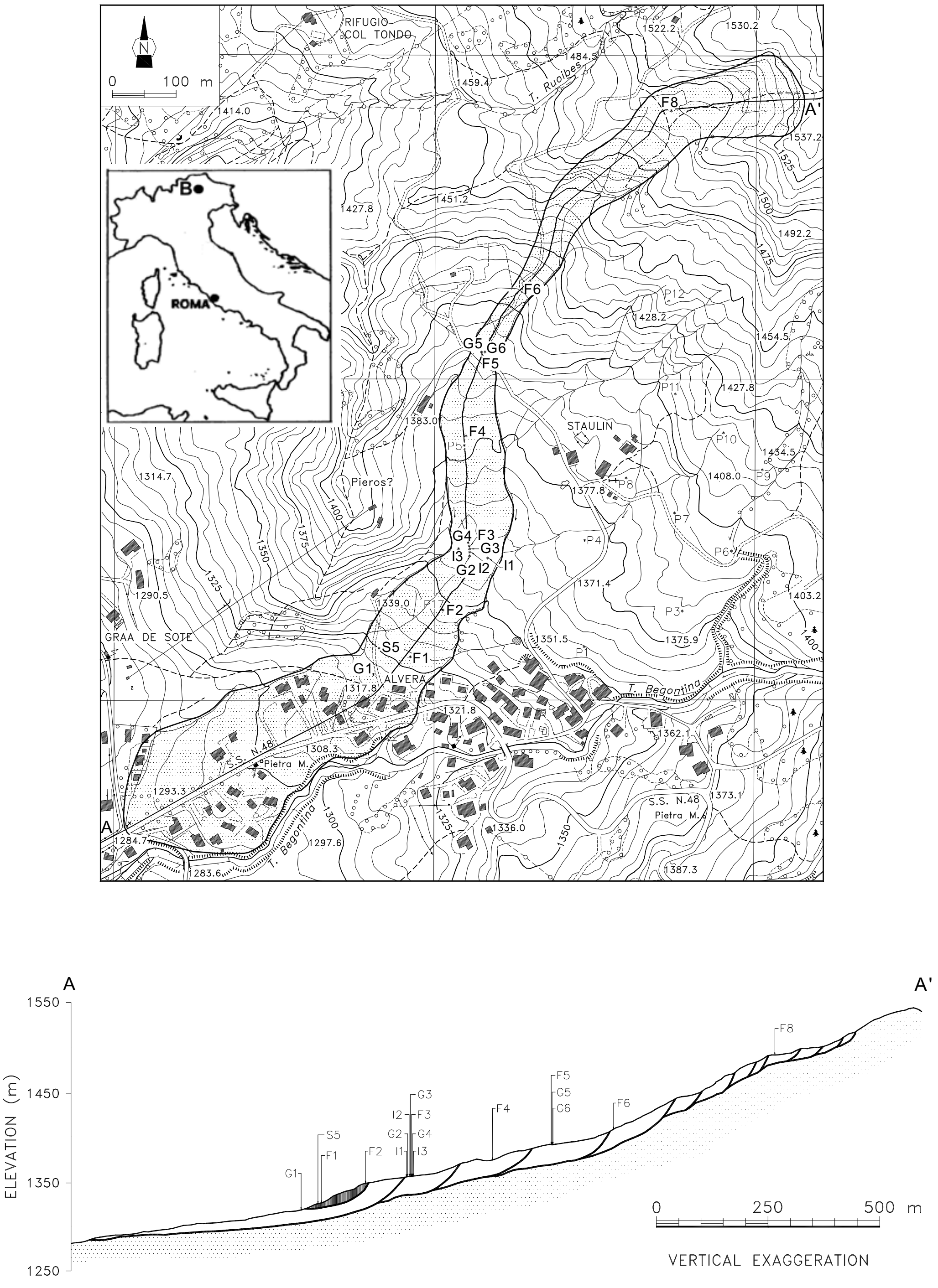

Figure 4. Location of the instrumentation and schematic longitudinal section of the Alverà mudslide.

Geotechnical laboratory tests were carried out on more than 40 samples from boreholes, excavation of drainage trenches and trial pits. The results showed significant differences between samples collected at any depth in the slope and those taken from the slip surface in a trial pit dug in the lower part of the Alverà mudslide. The characteristics of the samples are listed in Table 2.

Table 2. Alverà mudslide: geothecnical characteristics of the materials

Samples location	CF (%)	W_l (%)	I_p (%)	γ_{sat} (kN/m3)	ϕ_r (degree)
Any depth in the slope	30-36	29.7-115.0	15.5-70.0	18.73	14.0-26.0
Slip surface	56-71	69.3-99.1	29.6-51.1	18.73	9.0-15.9

3 THE LANDSLIDES MECHANISM

The mechanism of the Sant'Agata Feltria and the climatic conditions that cause instability can be outlined as follows.

It has been found that in the mountains, which are uphill of the village (Fig. 1), the Oligocene sandstones "floating" over the scaly clays seem to be affected by deep-seated gravitational movements.

These deformations gave origin to steps and trenches mainly trending N-S or NNE-SSW which disconnected the huge lithoid slab (the plateau) into minor parts. These parts continued to supply the mudslide with material.

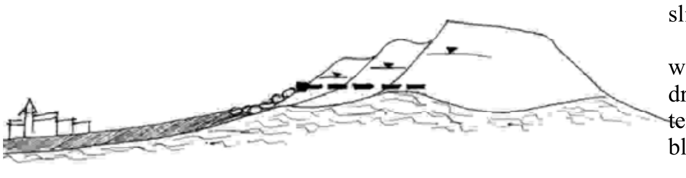

Figure 5. Schematic cross section in the landslide uphill area with indication of the deep drainage system planned.

In fact, large portions of the plateau (more than 200 metres thick, as detected by means of deep boreholes) tend to detach from the top, forming very large and deep rotational landslides (Fig. 5), favouring the formation of small lakes and ponds in the counter-sloping areas.

These landslides, formed by very large blocks of sandstones, overload the plastic clays below, causing undrained shear strength conditions in them.

As a result different lobes of clay tend to move and converge toward a unique channel of mudslide (Fig. 1).

The clay mudslide is not very thick (only a few metres), but it proceeds very quickly downhill, creating other overloads to the approaching clayey strata found along its path.

At the very end a continuous flow of soil takes place and only after reaching the natural drainage at its base and in the sandstone portions already collapsed uphill (the engine of the landslide) does the mudslide stop.

The uphill sandstone plateau corresponds to a huge natural water tank (Fig. 5). The measurements taken in the boreholes drilled at the top, in the framework of the overall monitoring system installed all through the mudslide, give a very high water table.

Under these conditions a continuous groundwater flow supplies the uphill landslide bodies, maintaining them at the limit of equilibrium.

Looking through the rainfall recordings it is quite evident that the landslide movements mostly coincides with periods of long-lasting and intense rainfall (Figs. 6, 7).

The event of 1934 demonstrated that the cumulative rainfall over 8 months can cause the sudden remobilization of the landslide.

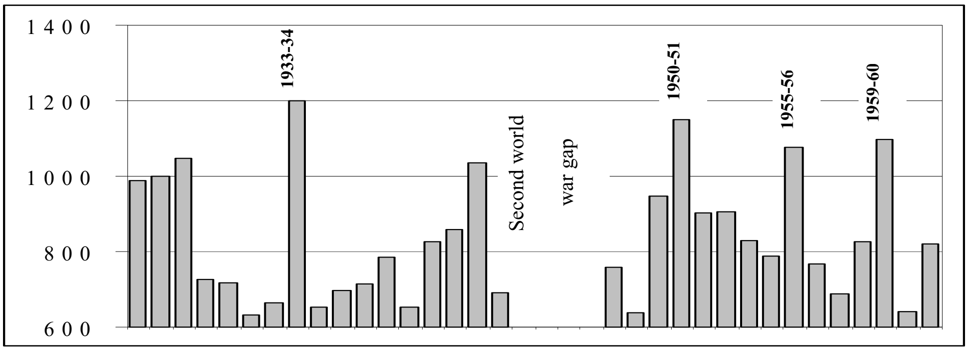

Figure 6. Series of the rainfall accumulated over 8 months (from August to March) in the period 1926-1962.

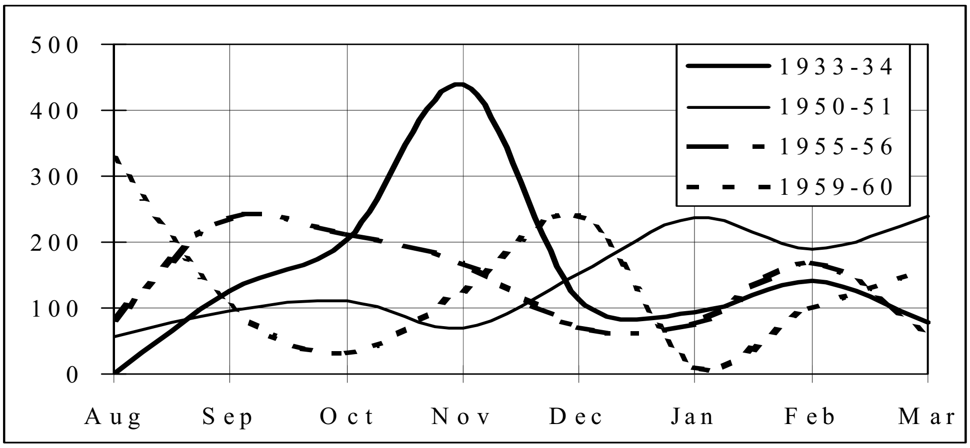

Figure 7. Monthly rainfall trend in the most critical periods shown in Figure 5; the 1933-34 trend seems to be responsible for the great landslide event of March 1934.

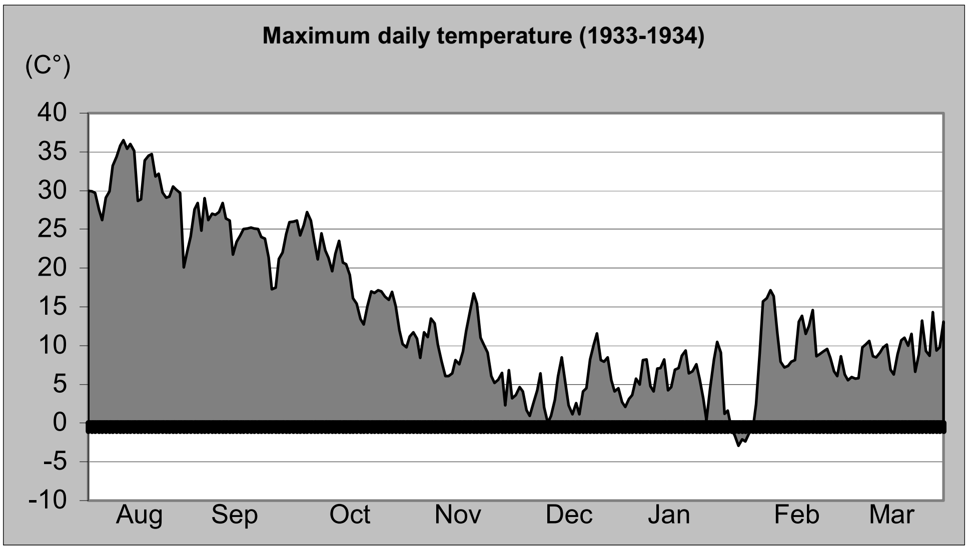

Figure 8. Maximum daily temperatures recorded at Verghereto meteorological station (812 m asl)

In fact, we have observed that starting from August 1933 until March 1934 a very large amount of rainfall occurred (1200 mm).

The analysis proceeded taking into account all the series of the rainfall accumulated over 8 months (from August to March) during the period 1926-1962.

But, in this same period at least other 3 similar values of cumulative rainfall were recorded, as clearly shown in Figure 6.

The point was that no important landslide events renewed in correspondence with these periods.

Under these conditions the analysis of each critical situation (shown in Fig. 6) continued taking into account the temporal distribution of the values of the monthly rainfall over the same period of 8 months starting from August and stopping in March (Fig.7).

In this way we found out that the temporal trend, in the 8 months preceding the 1934 landslide, shows a shape of the curve which is very different from the other situations analysed.

Moreover, the analysis of the air temperatures (over the same 8 month period) recorded in 1933-34 showed a very mild winter. In fact, the daily maximum temperatures observed at a meteorological station (Verghereto), located nearby the village, but at a higher elevation (812 m. asl), gave values always above 0°C (Fig. 8).

This definitely implies that the overall precipitation in that period was only rainfall and also that, in total absence of frozen soil surface, all this water could easily and continuously infiltrate at depth.

Therefore, we can conclude that all the climate recordings preceding the 1934 landslide event were very unusual and very favourable to induce critical groundwater conditions in the soil mass.

The Alverà mudslide is instead sensitive to climatic fluctuations occurring even in the short-term. The relatively long term monitoring carried out for many years has been allowed to detect the groundwater table thresholds working in the mudslide (Angeli 1992, Angeli et al. 1996b).

The landslide shows an advanced evolution stage characterised by geometrical features which do not change significantly in the short term (Fig. 4). It therefore shows slow but continuous channalised displacements which may have considerable acceleration only in concomitance with critical pluviometric events all over the area. Consequently, the watertable is usually very close to the ground surface, with limited fluctuations during these meteorological events. The piezometric response to pluviometric input has been estimated at less than five hours. This means that within the landslide body there are preferential flow paths for infiltration water owing to the numerous subvertical fractures present in the most superficial portion of the unstable mass.

This advanced evolutional stage of the mudslide is evident also from the geomorphological point of view, with three zones characterised by different slope gradients, approximately corresponding to an uphill compression area, an extension area in the central part and again a compression area in the lower part. The uphill area, which corresponds to the source area, is characterised by the presence of shallow roto-translational slides in successive steps. In the central area rather deep roto-translational slides are found, similarly to the lower mudslide part. On the whole, the envelope of all the slide surfaces may be considered as a single surface following approximately the trend of the ground surface (Fig. 4).

Comparing all the geomorphological observations, the topographic surveys, the recognition of weak zones inside the borehole cores (confirmed also by shear strength tests on the materials) and the deformation rates measured in the inclinometer tubes, it was possible to define in detail the geometry of the various blocks making up the mudslide body. It was also possible to

make a clear distinction between a main landslide body with thickness of 18 to 25 m and a secondary slab-type body (5 m thick) overlapping the main one in the lower part; since the latter is sufficiently long it may be considered as an infinite slope (Fig. 4).

All the above information collected during the past few years on the evolutional mechanism of this mudslide has then allowed the definition of a numerical model which can accurately reproduce the instability processes in progress (Angeli et al. 1996b).

4 FINAL REMARKS

The main result obtained by the geological and geotechnical studies carried out in the mudslides of Sant'Agata Feltria and Alverà is represented by the detection of the instability mechanism operating in the landslide masses.

The mudslide of Sant'Agata Feltria is characterised by a huge sandstone plateau hanging on the clay slope on which the village is located. Large blocks of sandstone tend to detach themselves from the plateau and overcharge the plastic clays below. At this stage the overloading creates undrained shear strength conditions in clays and a first portion of clay tend to move down hill, overcharging other clayey areas. The movement tends to transfer from the top to the bottom of the slope showing itself as a continuous flow moving on a relatively shallow slip surface (5-10 m) for a very long path (5.4 km). The movement seems to be triggered by unusual climatic conditions that occur every 30-40 years in the last two centuries as demonstrated by the analysis of long series of rainfall and temperature data.

The analysis of the rainfall series gave us a simple but effective tool to design control works in such a large area and showed that the distribution over selected periods of 8 months preceding the landslide occurred in March 1934 was very dangerous and capable of filling up very rapidly the uphill natural tank (the sandstone plateau).

The rapidity of this last process definitely prevented the possibility of dissipating the water pressures that can arise inside the landslide mass.

This lack in the natural drainage has proved to be crucial for the instability conditions of the whole landslide.

The Alverà mudslide is characterised by a long chain of landslide bodies (1.5 km long). Its geometry has reached a semistable configuration. Under these conditions the mudslide is influenced only by groundwater table fluctuations. For the above reasons only very strong precipitation can cause significant displacements. Because it is located in a mountain area the role of snow precipitation tend often to overcome the importance even of prolonged rainfall. It is the phenomenon of the snow melting occurring in early spring to supply the water table and to cause significant movements. The most important result of the long-term monitoring is provided by the recognition of the pore pressure threshold values along the slip surface.

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