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The “unusual” Ca’ Bonettini landslide (Province of Modena, Italy)

Abstract
In September 2003, in concomitance with a weak seismic shock, a landslide took place in the River Panaro valley, in the municipality of Marano (Province of Modena, northern Italy). The anomaly of this slope movement consisted in the fact that, although the mobilised soils were mainly argillaceous, the activation occurred at the end of a long drought period, whereas, usually, these types of landslides are recorded in the wet seasons, when the soil is saturated with water. After examining the geological and physical-mechanical characteristics of the formations making up the slope, the causes of this landslide are discussed in relation with man’s activities and the seismic tremor recorded. Finally, the most suitable remedial measures for slope stabilisation are suggested.

Riassunto
Nel settembre 2003, in concomitanza con una debole scossa sismica, si è verificata una frana nella valle del Panaro, in località Ca’ Bonettini nel Comune di Marano (Provincia di Modena). La singolarità di questo movimento franoso risiede nel fatto che, nonostante i terreni mobilizzati fossero prevalentemente argillosi, l’attivazione si è verificata alla fine di un lungo periodo siccitoso; mentre, solitamente, le frane in argilla avvengono nelle stagioni maggiormente piovose quando il suolo è saturo d’acqua. Dopo avere esaminato le caratteristiche geologiche e fisico-meccaniche dei terreni coinvolti dalla frana, si individuano le cause del movimento in relazione alle attività antropiche e allo scuotimento sismico subito dall’area, e gli interventi atti a stabilizzare il versante in frana.

Key words: *landslides, Northern Apennines, geomechanical characterisation*

Parole chiave: *frane, Appennino settentrionale, caratterizzazione geomeccanica*

Introduction

Early on 15th September 2003 a slope movement took place near Ca’ Bonettini, a group of houses in the Municipality of Marano sul Panaro (Modena Apennine hills), on the left-hand side of the River Panaro valley (Fig. 1). According to seismological data, an earthquake, VII-VIII degree MCS, 5.2 magnitude, was recorded late on 14th September 2003 in the nearby Bologna Apennines.

The anomalous aspect about this landslide is that although it took place in clayey materials, it occurred towards the end of a long summer drought period, with extremely low precipitation values during the months of June, July and August all over the province of Modena (Fazlagic *et al.*, 2003), when argillaceous soils were particularly hard and brittle due to prolongued desiccation.

The Ca’ Bonettini landslide showed an average displacement velocity of about 0.4 m/h, and affected a slope made up of “Argille Varicolori” and “Argille a Palombini” formations (Upper Cretaceous). The accumulation material partially obstructed the carriageway of the Panaro valley

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provincial road, requiring the immediate intervention of the technical services of the Modena Province. Another reactivation took place on 22nd February 2004, after intense precipitation in the months of January and February occurring all over this portion of the Northern Apennines.
From a classification viewpoint, this landslide is a complex movement consisting of earth slides and earth flows, with moderate displacement velocity (Cruden & Varnes, 1996). The activation of September 2003 took place along a 288 m long portion of slope and involved an area of some 43,000 m^2, with a surface of rupture located at a depth of 15-24 m (Tab. 1), as was ascertained by mechanical boreholes and seismic prospecting.

Fig. 1 – Panoramic view of the slope where the Ca' Bonettini landslide took place. Broken lines represent the landslide's crown and body (courtesy of D. Castaldini)

Geological and geomorphological setting

The territory of Marano is located in the outer part of the Apennine chain and is prevalently characterised by low, mild hills (altitude 140 to 350 m a.s.l.) in proximity with the southern Po Plain. Its main features are the course of the River Panaro on the valley floor and the presence of several landslide bodies (mostly dormant) along the hill slopes.
In the study area the formations cropping out are prevalently chaotic, argillaceous and, to a lesser extent, arenaceous rock types belonging to the allochthonous Ligurian Units. In particular, the "Argille a Palombini" clay shales, the "Arenarie di Scabiazza" sandstones and the "Argille Varicolori di Cassio" clay shales are here found. They all belong to the Cassio Tectonic Unit, Panaro Tectonic Sub-unit (Servizio Geologico d'Italia, 2002).
The Palombini shales (Lower-Upper Cretaceous) crop out extensively in the study area, since they are dominant in this stretch of the Panaro valley. These dark grey clay shales are originally intercalated with calcilutite layers but appear intensely deformed by tectonic stresses and their original attitude is nearly always completely obliterated.

Topographic location of the study area	
C.T.R. Emilia-Romagna Region (Italy), 1:10,000 scale:	
topographic sections nos. 219160 (Guiglia) and 219120 (Marano sul Panaro)	
Geographical coordinates of the landslide body: lat. 44°26'52" N; long. 10°56'43" E	
Catchment basin:	River Panaro
Landslide morphometry	
- slope angle:	15÷20°
- difference in elevation:	68 m
- altitude at crown:	223 m
- altitude at tip:	155 m
- length (L):	288 m
- maximum width (W):	225 m
- L/W ratio:	1.28
- depth of surface of rupture:	15÷24 m
- approximate area:	$4.3 \cdot 10^4$ m^2
- approximate volume:	$7.5 \cdot 10^5$ m^3
Landslide classification (according to Cruden & Varnes, 1996):	
Compound (rotational-translational) earth slide and earth flow	

Tab. 1 – Location, morphometric features and classification of the "Ca' Bonettini" landslide

The Scabiazza Sandstones (Upper Cretaceous), which in the Northern Apennines are closely associated with the Cassio Varicoloured clay shales by means of lateral heteropic changes, are made up of thin-layered, arenaceous-pelitic turbidites; they often crop out as intensely tectonised, disrupted beds. In the mid-Panaro valley this formation is in direct contact with the Palombini clay shales by means of a highly tectonised laminated surface.
Also the Cassio Varicoloured shales (Upper Cretaceous) are lithologically heterogeneous, being made up of alternating reddish, grey and blackish fissile clayey layers, cropping out as thin beds intercalated with turbidite bodies and calcilutites. These clay shales are highly tectonised and only very seldom do they preserve their original attitude. Their lower stratigraphic boundary with the Palombini shales is always intensely deformed.
All these formations have no relevance from the hydrogeological viewpoint, since they are mainly made up of very low-permeability clayey rock types which allow only weak surface seepage due to widespread fissures.
According to the Marinos & Hoek (2001) geotechnical flysch classification, all the rock types here described are defined as heterogeneous rock/soil masses or, according to Esu (1977), complex. The Scabiazza Sandstones, which are tectonically deformed, intensively folded/faulted sandstone layers alternating with thin levels of sheared clay shales, are defined as F type ("poor") rock masses with a Geological Strength Index (GSI) of 25÷35. On the other hand, the Palombini and Varicoloured shales, which are tectonically deformed clay shales forming a chaotic structure with layers of sandstone or limestone dismembered into small rock pieces, are defined as H type ("poor" to "very poor") rock masses with a GSI of 10÷20. Tab. 2 summarises the main parameters obtained by applying the Hoek-Brown criterion (Hoek & Brown, 1997) to the study area. It should be stressed, though, that c' and φ' values are functions of the overload the rock type is submitted to and pertain to theoretically "intact" rock samples. Therefore, assuming a standard depth of some 20 m, that is with a high degree of confinement, the shear strength angles obtained are much higher than the values resulting from laboratory tests carried out on clay shale samples collected from the first 20 m below the soil surface (Tab. 3).

From the standpoint of the response to seismic shocks, the elastic behaviour of the Varicoloured and Palombini shales – which are the formations directly affected by the Ca' Bonettini landslide – is ascertained on the basis of the value of the elastic modulus (Em = 500÷1000 MPa), which shows geomechanical features typical of rather poor, strongly tectonised scaly clay shales affected by pervasive discontinuities at any scale.

Formation	**Type of flysch** (G.S.I. rating)	**Mohr-Coulomb parameters**		**Rock mass parameters** (according to the Hoek-Brown criterion)			
		φ' (°)	**c' (MPa)**	**σ_t (MPa)**	**σ_c (MPa)**	**σ_{cm} (MPa)**	**E_m (MPa)**
Scabiazza Sandstones	F = 25÷35 (poor)	50.80	0.22	-0.01÷-0.1	1.0÷3.0	3.0÷10	1000÷5000
Palombini Shales and Varicoloured Shales	H =10÷20 (poor to very poor)	31.10	0.07	-0.005÷ -0,01	0.1÷1.0	1.0÷3.0	500÷1000

Tab. 2 – Main rock mass features of the formations cropping out in the Ca' Bonettini landslide area obtained by using the Hoek & Brown (1997) criterion. Legend: φ' = effective shear strength angle; c' = effective cohesion; σ_t = tensile strength; σ_c = uniaxial compressive strength; σ_{cm} = global strength; E_m = Elastic modulus (after Mandrone, 2004)

Sample / depth	**w (%)**	**w_L (%)**	**w_P (%)**	**w_S (%)**	**I_p (%)**	**I_c**	**γ (kN/m^3)**	**CF (%)**	**A_c**	**φ' (°)**	**c' (MPa)**	**c_u (MPa)**
C1-S1 7-7.5 m	17.8	40.7	21.2	17.0	19.5	1.17	20.5	53.7	0.36	17.9	0.152	0.292
C1-S1 10-10.5 m	19.1	43.0	22.0	16.9	21.0	1.14	21.0	57.3	0.36	17.3	0.147	0.328
C1-S2 3-3.5 m	16.2	38.0	25.0	16.8	13.0	1.67	20.4	51.2	0.25	19.8	0.188	0.350
C2-S1 9-9.5 m	18.6	38.9	20.1	17.2	18.8	1.08	20.9	48.6	0.39	18.0	0.185	0.334
C2-S1 17.5-18 m	19.7	35.0	23.0	17.5	12.0	1.27	20.3	49.8	0.24	18.3	0.345	0.515
C3-S3 11-11.5 m	13.9	39.5	20.3	16.2	19.2	1.33	21.4	48.9	0.39	19.3	0.233	0.520
C4-S3 19-19.5 m	12.5	36.7	20.1	15.9	16.6	1.45	20.7	50.4	0.33	19.6	0.289	0.456

Tab. 3 – Geotechnical properties and physico-mechanical characteristics of bore-cored samples obtained from laboratory tests. Symbols: w = water content; w_L = liquid limit; w_P = plastic limit; w_S = shrinkage limit; I_p = plasticity index; I_c = consistency index; γ = bulk unit weight; CF = clay fraction; A_c = activity index; φ' = effective shear strength angle; c' = effective cohesion; c_u = undrained cohesion [N.B. shear strength parameters were obtained by means of direct shear tests (φ' and c') and unconfined compression tests (c_u), modified after Maccaferri, 2003]

Landslide type and predisposing causes

As confirmed by photographs and aerial images from the 1960s-70s, a dormant landslide body was already present along the slope where the Ca' Bonettini landslide of 15th September 2003 took place. In those years the slope's lower portion was cultivated whereas its upper part was partially covered by scanty vegetation (Fig. 2). Therefore, in accordance with the great majority of mass wasting processes occurring in the Northern Apennines, also this landslide is a reactivation of a previous movement of unknown origin, probably going back to thousands of years ago, at the end of the last Ice Age (10,000-9,000 yrs BP), when extremely severe hydrogeological conditions and intense weathering and erosional processes characterised these mountain slopes (Bertolini & Pellegrini, 2001).

Fig. 2 – General view of the Ca' Bonettini slope on the left-hand side of the Panaro Valley showing dormant landslide bodies in September 1969 (courtesy of M. Pellegrini)

The 2003 Ca' Bonettini landslide affected a 288 m long slope made up entirely of clayey soils with an average displacement velocity of about 0.4 m/h. The landslide crown stretched over a length of about 150 m in a NE-SW direction, at an altitude of 200 to 225 m. The movement involved an area of some 43,000 m^2, with a surface of rupture located at a depth of 15-24 m (Tab. 1), as was ascertained by mechanical boreholes and seismic investigations (Maccaferri, 2003). The accumulation material of the 15th September landslide partially obstructed the Panaro valley provincial road. The immediate intervention of the technical services of the Modena Province was therefore necessary. The first remedial measures consisted in remodelling the landslide toe with the insertion of drain pipes to reduce pore water pressures. Soon after the completion of these works the movement ceased, but after five months, on 22nd February 2004, a second reactivation took place, after intense precipitation occurring in the months of January and February all over this portion of the Northern Apennines (Ministero LL. PP., 2004).
From a classification viewpoint, this landslide is defined as compound (rotational-translational) earth slides and, locally, earth flows (Cruden & Varnes, 1996) with slow to moderate displacement velocity (Fig. 3).
In the general framework of the slope movements affecting clayey materials in the basin of the River Panaro, the 2003 Ca' Bonettini landslide showed a rather anomalous and statistically rare behaviour since it occurred towards the end of a long summer drought period, caused by three full months of absence of precipitation, when the soil had become particularly hard and brittle. Therefore, the absorption of high amounts of infiltration water and the consequent soil plasticisation – which so frequently determine the onset of slope movements in this portion of the Apennine chain – played no role in the reactivation of this landslide. Nevertheless, the long summer drought had produced considerable shrinkage of the clayey soils making up the slope, with the formation of deep and widespread fissures all over the landslide body which was dismembered into several blocks with considerable reduction of its overall cohesion. As a consequence, the already precarious stability conditions of the slope further declined predisposing the pre-existing landslide body to new movements.

Fig. 3 – The source area of the Ca' Bonettini landslide: slip surfaces and open ground fissures (September 2003)

Another predisposition cause for landsliding should also be considered. Since the mid-1960s the area near the foot of the Ca' Bonettini landslide body, in proximity to the valley floor, has been subject to human activities, mainly consisting of industrial and office buildings as witnessed by photographs taken in that period (cf. Fig. 2). Late in August 2003, just weeks before the landslide's first reactivation, building activities were extended towards the landslide foot with the construction of another two buildings, preceded by considerable morphological changes with the removal of large amounts of earth to make room for new constructions (Fig. 4). These works further reduced the stability of the slope, since it is well known that the removal of material from the zone of accumulation of a dormant landslide leads inevitably to a general decline of stability conditions.

Fig. 4 – Industrial buildings recently constructed at the foot of the Ca' Bonettini landslide (March 2004)

Relationship with earthquakes

According to seismological data, a VII-VIII degrees MCS and 5.2 magnitude earthquake was recorded at 21:42 hours (GMT time) on 14th September 2003, with its epicentre near the village of Monghidoro (Bologna Apennines), some 35 km SE of the study area. The earthquake focus – which is located along a belt of crustal seismicity characterised by a N-S compression affecting the external part of the Apennine chain (i.e., towards the Po Plain) – was estimated at a depth of 18-20 km (Ist. Naz. Geofisica e Vulcanologia, 2004). After the main shock other seismic tremors of lower intensity were recorded in the following hours and days, until 16th September 2003. According to eye-witnesses, the Ca' Bonettini landslide resumed activity early on 15th September, just a few hours after the main 5.2 magnitude shock. Nevertheless, considering the distance of the study area from the epicentre and the fact that locally the quake was not felt by the population but was recorded only at instrument level, it is unlikely that a low-energy shock might be considered as the main, intrinsic cause of landslide reactivation.

Field observations, subsurface investigations and laboratory tests seem to indicate that the predisposing causes of the Ca' Bonettini landslide could be found in the deep shrinkage fissures that dismembered the whole clayey slope as a consequence of a three-month long drought period, with a progressive decline of shear strength parameters. Nevertheless, back analyses carried out on the landslide body (Fantoni, 2004) show that in the particular climatic conditions of September 2003 (absence of infiltration water and piezometric level) the factor of stability is higher than 1.3. At this point, considering the weakness of the seismic shock, the most important role in further reducing stability must have been played by the major works at the foot of the landslide body, with the removal of large amounts of earth, which were carried out without considering that the area chosen for industrial development corresponded to the foot of a dormant landslide.

Therefore, the 14th September low-intensity earthquake was only the triggering cause of a slope movement which would have probably started all the same in a matter of a few days or weeks as the removal of material from the landslide foot continued as planned.

On the contrary, the second reactivation of 22nd February 2004 – which continued in a discontinuous way for all the month of March – after intense precipitation occurring in January and February had caused considerable water absorption by the landslide body, showed all the typical features of an earth flow with plasticisation of the material involved and low displacement velocity (20-30 mm/day), as witnessed by inclinometer measurements (Maccaferri, 2003). In these "wet" conditions, the factor of stability decreases to the unacceptable value of 1.085 (Fantoni, 2004).

Remedial measures

After the first reactivation and the analysis of seismographic and other instrument data, it was clear that the causes of slope instability were to be found in the excavation and building activities carried out at the foot of the landslide. Therefore, a series of remedial measures was planned in order to increase stability and, at the same time, safeguard the new constructions directly threatened by the movement. The first consolidation works consisted in remodelling the landslide toe with the insertion of drain pipes to reduce pore water pressures, but it was soon obvious that these measures were not sufficient to reinstate the lost stability. Subsequently, a containment wall anchored to the ground by means of 50 m long piles, was constructed uphill of the new buildings (Fig. 5) and surface drains were placed all over the landslide body in order to reduce water absorption.

Although these interventions have considerably reduced the displacement rate of the Ca' Bonettini landslide, the risk of new movements still persists as witnessed by inclinometer data. Therefore, in order to guarantee the survival of the inconveniently constructed new industrial area, adequate monitoring systems must be constantly activated and other, more expensive measures will probably have to be implemented in the near future.

Fig. 5 – Slope cut at the foot of the Ca' Bonettini landslide and containment wall (March 2004)

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