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Hydro-mechanical characterisation of flysch-derived colluvial slopes affected by rainfall-induced landslide

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ABSTRACT: Landslides involving thick channelised colluvial slopes (5–10 m) induced by heavy rainfall pose severe threats to human settlements due to their potential for repeated failures and long run-out distances caused by fluidisation of the mobilised material. Channelised landslide deposits often exhibit complex 3D geometries and discontinuously superimposed soil layers with varying hydro-mechanical properties, resulting in irregular permeability thresholds that often align with pre-existing sliding surfaces. In such a complex geological context, the soil sampling and testing aimed at investigating the hydro-mechanical properties of the involved materials shall be performed considering the specific stratigraphy of the landslide deposit, in order to effectively understand the slope failure mechanism. This study presents selected laboratory test results on flysch-derived colluvial samples from the channelised landslide in Sedilis, Friuli Venezia Giulia, NE Italy. Key analyses included grain size distribution, index properties, and results from conventional direct shear and ring shear apparatus tests conducted under different testing and confining pressure conditions. The tested colluvial materials were highly heterogeneous, ranging from clayey silts (87% of fine fraction, i.e. particle size less than 63μm) to silty-clayey gravels (47% of coarse fraction) with low-to-medium plasticity and peak friction angle values between 26–38°. Findings from the study provide insights into the soil's shear behaviour and propensity to fluidise, which help understanding the mechanical processes driving slope instability of thick channelised colluvial deposits.

KEYWORDS: Colluvial deposit, flysch, soil slip, rainfall infiltration, fluidisation.

1 INTRODUCTION

In the mountain environment, slopes made up of colluvial soils are frequently involved in rainfall-induced landslides that pose severe threats to human settlements due to their potential for repeated failures and long run-out distances caused by fluidisation of the mobilised material (Froude & Petley 2018; Bellugi et al. 2021; Paronuzzi & Bolla 2023). Colluvial soils are typically made up of highly heterogeneous unconsolidated sediments ranging from clayey loam to rock fragments (Turner 1996; Goudie 2004). Flysch-like rock masses that include rhythmic alternations of marl, shale, marly limestone, sandstone and siltstone are particularly prone to generating colluvial deposits due to chemical/physical weathering and a combination of processes including rainwash, sheet erosion, soil creep and shallow landslides (Millar 2014; Mücher et al. 2018; Zádarová et al. 2023).

Flysch-formed reliefs tend to originate a complex geomorphological system that is characterised by numerous creeks and gullies where landslide deposits accumulate due to the repeated instability of the upper slopes (Del Fabbro et al. 2024). Active slopes characterised by recurrent failures, also including soil slide-flows, can form channelised deposits where distinct and superimposed landslide masses accumulate within pre-existing creeks or gullies. Recurrent shallow slope failures can lead to the superimposition of a debris cover on top of an underlying colluvial deposit caused by an older landslide event, thus reaching a considerable overall thickness (5–10 m). As a result, channelised landslide deposits are irregularly stratified, including a number of soil layers in the form of discontinuous lenses with varying hydrological and geomechanical properties.

Another important factor controlling the instability processes of these channelised slopes covered by thick colluvium is hydrogeology. In fact, deep-water circulation occurs within buried gullies and is strongly conditioned by marked permeability thresholds represented by the basal contact between the colluvial cover and the sandstone-marly bedrock as well as by superimposed soil lenses with highly different hydrological characteristics, which often align with pre-existing sliding surfaces. As a result, the rainfall infiltration and water seepage processes through the colluvial deposit, which are responsible for the decrease in soil suction and the subsequent increase in pore-water pressures that can lead to slope failure, are strongly influenced by the geomechanical and hydraulic characteristics of the involved materials as well as by the geological origin and specific stratigraphy of the soil deposit (Assouline 2013; Peranić et al. 2020, 2021; Paronuzzi et al. 2022, 2024). The irregular soil stratification influences the pore pressure distribution within the colluvial deposit and is responsible for the fluidisation of the involved materials and the activation of slope failure.

Another awkward issue is that related to the intrinsic heterogeneity of colluvial materials, especially those involved in recurrent landsliding, which makes their sampling and testing challenging, also considering the problem related to the scale effect (Wästerlund 2020; Stefanow & Dudziński 2021). Their hydro-mechanical characterisation requires an approach based on both field and laboratory investigations, adopting various test equipment and considering samples of different size in both intact and remoulded conditions.

To contribute to a more profound knowledge of the geomechanical and hydraulic characteristics of flysch-derived colluvial soils, this study presents selected laboratory test results on colluvial samples from a channelised landslide that occurred in Sedilis, Friuli Venezia Giulia (FVG), NE Italy (Figure 1). Findings from the study provide insights into the soil's shear behaviour and propensity to fluidise, which help understanding the mechanical processes driving slope instability of thick channelised colluvial deposits.

2 CASE STUDY: THE SEDILIS SOIL SLIDE- FLOW

The analysed case study is located in the pre-alpine area of FVG (southeastern sector of the Alps), which is dominated by surface deposits made up of colluvial soils due to the occurrence of rock masses formed by alternating arenaceous-pelitic sequences belonging to the flysch of Friuli Formation (upper Campanian-Lutetian in age). Flysch reliefs in the surroundings of Sedilis are characterised by a complex geomorphological system related to a closely spaced alternation of ridges and incised gullies, which results in the occurrence of multifaceted slopes. Soil slopes made up of colluvial materials have variable inclinations, ranging between sub-horizontal terraces and 35–40°-inclined slopes.

The pre-alpine area of FVG is dominated by a wet and rainy climate due to the influx of winds that are rich in humidity that blow from the close Adriatic Sea. The study area is frequently hit by rainstorms characterised by a high intensity (I = 40–100 mm/h) and limited duration (D = 1–6 h), which mainly occur during the wet season (September-November) or during the spring (May-June). Some extreme hydrological events have been responsible for the activation of dozens of shallow slope failures over time. In most cases, these landslides were characterised by an initial sliding of a colluvium mass and a subsequent fluidisation of the material, being therefore classified as soil slide-flows. The investigated slope is related to a thick channelised landslide deposit that is the result of repeated slide-flows of colluvial material that buried a gully in the flysch range. The most important slide event occurred in 1998, which was followed by a partial reactivation in 2014 (Figures 1 and 2a).

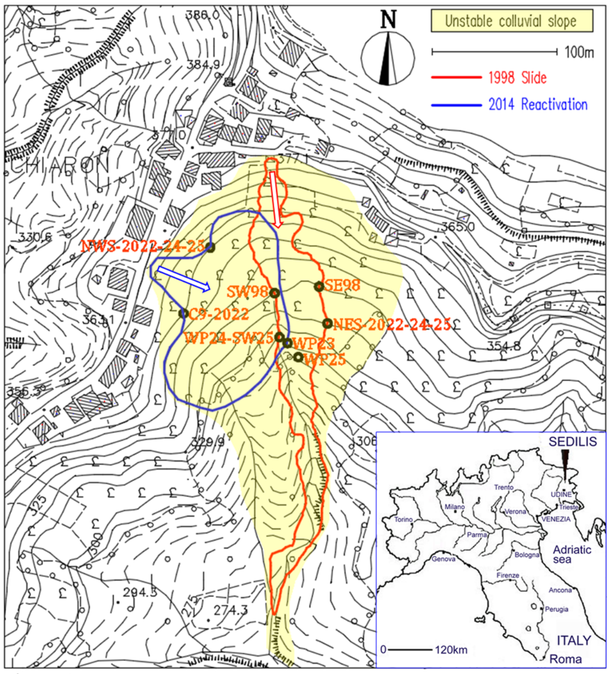

Figure 1. Planimetric sketch of the Sedilis unstable slope showing the 1998 slide-earth flow (in red) and the 2014 partial reactivation (in blue). The locations of field testing and soil sampling are indicated in red text.

2.1 *Stratigraphy of the colluvial deposit*

An engineering–geological survey was carried out on the Sedilis channelised landslide area both after the 1998 slide and the 2014 reactivation events, in order to investigate the stratigraphy of the colluvial deposit. During fieldwork, some key outcrops in correspondence with landslide scarps were investigated in detail excavating some trenches to point out the stratigraphic contacts within the colluvial deposit. For each investigated outcrop, a stratigraphic analysis was performed, identifying and measuring the thickness of the different soil layers.

Owing to the characteristic 3D geometry of the buried gully, the investigated colluvial deposit has a very variable thickness, with an average value of 7–8 m. The maximum ascertained thickness is reached in the median zone of the landslide deposit, in correspondence with its axis. The typical texture of flysch-derived colluvial soils is characterised by an abundant fine matrix mixed with a skeleton made up of marl and sandstone fragments from the parent rock mass. According to evidence obtained from the various analysed scarps, the colluvial deposit is characterised by a very complex stratigraphy. An 8–10 m-high major scarp that is located close to the axis of the buried gully and was formed as a result of the 1998 slide pointed out the occurrence of several soil layers that overly the bedrock. The stratigraphic analysis also highlighted the presence of a pre-existing sliding surface that separates two superimposed colluvial deposits that are related to different landslide masses that were mobilised in the past (Figure 2b). Another scarp of lower height (4–5 m) that coincides with the western boundary of the slide area and was formed as a result of the 2014 reactivation, is characterised by three distinct soil layers: (i) a 30–50 cm thick organic topsoil, with abundant roots and macro-voids; (ii) an upper colluvial soil of highly variable thickness with a prevailing loamy matrix; (iii) an underlying colluvial soil made up of abundant angular fragments of marl and sandstone with a scant amount of loamy matrix.

Figure 2. a) Crown of the 1998 soil slide-flow, close to the village of Sedilis. b) Major scarp formed as a result of the 1998 slide showing a pre-existing sliding surface within the colluvial deposit (white arrows).

On the whole, the engineering–geological survey demonstrated that the channelised landslide deposit has a very complex stratigraphy, depending on the local geometry of the buried gully and the failure kinematics of previous landslide events. The thickness of the deposit is higher in correspondence with the gully axis, where distinct and superimposed landslide masses accumulated and are separated by pre-existing sliding surfaces.

3 HYDRO-MECHANICAL CHARACTERISATION OF COLLUVIAL SOILS

The field survey was also aimed at arranging some field tests to evaluate the in-situ vertical saturated hydraulic conductivity of the soil layers (variable head permeability tests) as well as at collecting soil samples to determine their geomechanical and hydrological properties in the laboratory. The soil sample collection was performed in order to minimise disturbance. Samples were collected from the landslide scarps in both intact and remoulded conditions. The colluvial soil testing was aimed at the assessment of their grain size distribution, Atterberg limits, plasticity and activity index, shear strength properties, moisture condition, matric suction, hydraulic conductivity and propensity to fluidise. Laboratory tests were performed in the Geotechnical and Engineering Geological Laboratory at the University of Udine (Italy) and the Geotechnical Laboratory at the Faculty of Civil Engineering, University of Rijeka (Croatia).

The results of grain size analyses for the natural samples are shown in Figure 3.

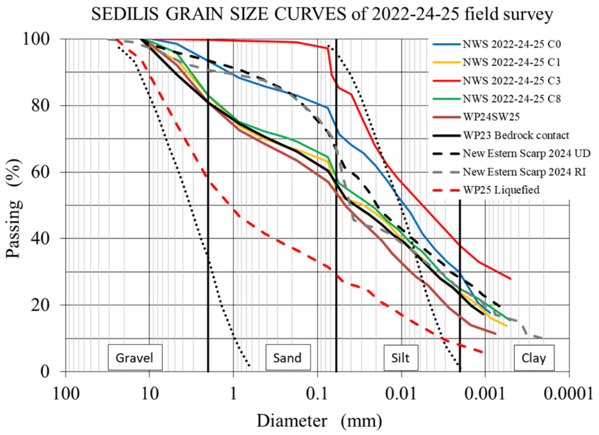

Figure 3. Grain size distribution curves of the colluvial soils that were sampled from the eastern and western scarps of the 1998 and 2014 slides.

Data on samples collected at different depths from the western scarp formed as a result of the 2014 reactivation (NWS 2022-24-25 and WP24-SW25 in Figure 1) pointed out that:

- the fine fraction (silt and clay) was predominant and generally ranged from 53% to 87%;
- the content of coarse fraction (gravel and sand) was considerable in all samples, in the range 13–47%;
- silt was the major fraction in all the analysed samples, ranging from 31% to 49% with a mean value of 39%;
- the clay fraction ranged from 16% to 38% with a mean value of 26%.

The grain size composition of the colluvial materials sampled from the eastern scarps was similar to that of the western scarp, confirming a prevailing silty fraction and the mean value of the clay fraction.

One sample that was collected at the basal contact with the flysch bedrock (WP23 in Figure 1) showed similar values of silt (33%) and fine fraction, i.e. clay- plus silt-size particles (56%), with a clay fraction close to the mean value (23%).

The grain size analyses also highlighted different contents for a sample that was collected in a fluidised state along the axis of the 1998 slide (WP25 in Figure 1). It was characterised by a high coarse fraction, i.e. sand- plus gravel-size particles (about 70%) and an overall content of silt and sand equal to 50%, which is usually related to a fluidisation susceptibility condition of a soil.

When considering the index and plasticity properties of the natural colluvial samples, their values were as follows:

- void index e = 0.58–1.16
- porosity n = 0.37–0.54
- natural water content w_n = 22–39%
- saturation degree S_R = 74–100%
- volumetric water content θ_w = 0.35–0.51
- bulk unit weight γ = 17.3–21.0 kN/m^3
- liquid limit w_L = 38–53%
- plastic limit w_P = 22–26%

All samples had a natural water content included between values of w_P and w_L, and this characterises the slow plastic deformation behaviour of soils. Some moisture profiles that were previously determined for the Sedilis slide (Del Fabbro et al. 2024) have been herein updated on the basis of new water content measurements (Figure 4). Values of the saturation degree confirmed a general curvilinear trend with an exponential-shaped curve, showing an increase in the saturation degree as the depth increases.

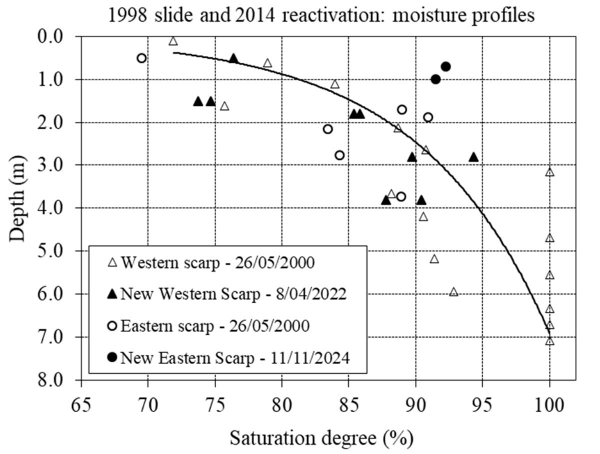

Figure 4. Moisture profiles of the colluvial soils that were measured at various time periods on the scarps of the 1998 slide and the 2014 reactivation.

Some suction measurements were carried out, for comparison purposes, both in-situ and in the laboratory on colluvial materials in partially saturated conditions (Figure 5). In-situ measurements were carried out with jet-fill tensiometers at different depths along the New Western Scarp that was surveyed in 2024. Field-measured suction values were in the range 4-12 kPa, without however, a clear decreasing trend as the depth increases. Suction measurements that were carried out in the laboratory with digital mini-tensiometers were equal to 4-6 kPa. The analysed samples were characterised by values of w_n lower than 30%.

Figure 5. Suction measurements that were carried out: a) in-situ with jet-fill tensiometers; and b) in the laboratory with digital mini-tensiometers.

One important aspect associated with the 1998 soil slide-flow is related to the soil fluidisation. During the field surveys that were carried out over time, evidence of fluidised soils was recognised over the slide area. In general, the soil types with a greater propensity to fluidise are the grained soils (mainly, fine gravelly-silty-sandy soils), but saturation conditions can play a key role in water absorption capacity. Furthermore, permeability also influences the capacity and velocity of the soils (especially stratified soils) to develop pore water overpressures (PWOPs), such as to bring them into fluidisation conditions. The PWOPs can increase for various reasons, but for slope instability processes, the most important are heavy rainfall and seismic actions, both of which may have served as a trigger for the Sedilis landslide.

Some geomechanical index parameters are useful for a preliminary assessment of the soil typology and the propensity to fluidise. The Approximate Mobility Index (AMI; Ellen and Fleming 1987) is defined as the ratio between the water content at saturation (w_{sat}) and the liquid limit (w_L), that is AMI = w_{sat}/w_L. When AMI > 1, the soil contains sufficient water to flow, and it is in a fluid state. The grain size limits for soils, differentiated on the basis of the uniformity coefficient (U_c) greater or less than 3.5, are identified in the Italian Technical Standard for Constructions (ITSC 2018). The colluvial materials samples from the Sedilis landslide were all characterised by $U_c > 3.5$. The limits are reported with black dot lines in Figure 2. The grain size curve of sample WP25 only (Figure 3) is placed almost entirely within the range identified by the limit curves, and its AMI was greater than 1, confirming the in-situ evidence of its fluidised state during sampling. For the samples characterised by higher clay contents, AMI was included between 0.5 < AMI < 1 (0.61–0.92 for the NES2024 and 0.52–0.84 per la NWS2022), thus indicating that the materials need to adsorb water in excess to the w_L to fluidise. This result confirms the conditions already investigated in previous surveys for the colluvial soils of the Sedilis area (Del Fabbro et al. 2024).

The liquidity index (I_L) and the consistency index (I_C) relate the natural water content with liquid and plastic limits, respectively, of the soil. These indexes describe the behaviour of fine soils by combining information on the consistency/liquidity classes and those of strength and compressibility. An increase in I_C corresponds to an increase in shear strength and a reduction in compressibility. The investigated colluvial silty-clayey soils generally had a soft-plastic or plastic consistency, with a consistency index ranging between $0.25 < I_C < 0.75$, which is associated to undrained shear strength (Cu) of 10 < Cu < 75 kPa. These values of undrained shear strength are confirmed by some in-situ measurements that were carried out with the pocket penetrometer and the vane shear, highlighting values of 15–54 kPa with a mean of 35 kPa.

The hydraulic properties of the colluvial soils were investigated in-situ using the variable head permeability tests along the scarps originated by the 2014 reactivation (C9-2022 and C8-NWS-2022) as well as by some tests, performed both at variable and constant head, at different depths of the NWS 2022-25. Field measurements pointed out that the top organic soil was characterised by a vertical hydraulic conductivity of 1.2×10^{-4} m/s, whereas the upper colluvial soil had a vertical permeability of 7.8×10^{-5} m/s. Laboratory measurements performed in oedometer at different consolidation pressures and saturated conditions, pointed out that:

- the increase in the vertical stress (2 kPa < σ_v < 100 kPa) caused a general decrease in the soil permeability;
- vertical permeability ($3 \times 10^{-6} < K_v < 1 \times 10^{-5}$ m/s) and horizontal hydraulic conductivity were very close for samples that were collected at both shallower and greater depths;
- vertical permeability values measured in-situ were always higher from those obtained in the laboratory, with differences between values up to an order of magnitude.

Two additional variable head permeability tests in oedometer with low vertical stresses (12.5 kPa < σ_v < 50 kPa) were performed on samples collected from the new eastern scarp of the 1998 landslide (NES2024) at a depth of 0.7 m. The results demonstrated that the increase in the vertical stress caused a slight decrease in the vertical soil permeability (K_v) from 3.8×10^{-6} m/s to 1.4×10^{-6} m/s, similarly to previous results (Del Fabbro et al. 2024).

When investigating the shear strength properties of the colluvial soils, conventional direct shear and ring shear tests were performed on both intact and remoulded samples. The peak shear strength values of intact samples, which were collected from the slide scarps, are summarised in Table 1. Tests were performed in the Casagrande square shear box (6 x 6 x 2 cm) with a normal stress (σ_v) varying between 50 < σ_v < 200 kPa and a rate of displacement of v = 0.01 mm/min.

Table 1. Values of the peak shear strength of the colluvial samples, measured with the Casagrande direct shear box (UD = Udine and RI = Rijeka).

Sample	Depth	Peak friction angle	Peak cohesion
NES-2024 - UD	0.7 m	25.8°	15.7 kPa
NES-2024 - RI	0.7 m	26.7°	10.5 kPa
WP24-SW25 - UD	0.3 m	26.5°	3.0 kPa
WP24-SW25 - RI	0.3 m	27.6°	15.3 kPa

The peak shear strength values for undisturbed natural samples from the New Eastern Scarp 2024 (NES-2024 in Table 1), which were obtained with the Casagrande shear box from two independent laboratories (Udine and Rijeka), were confirmed by an additional triaxial test that was performed in consolidated and undrained conditions (TXCIU) on samples with a height of 76 mm and a diameter of 38 mm. The results of the TXCIU test were $\phi'_p = 27.0°$ and $c'_p = 3.4$ kPa. According to the results obtained from the two laboratories, direct shear tests on intact samples collected from the New Western Scarp 2025 (WP24-SW25 in Table 1) highlighted close values of the peak friction angle but different values for the peak cohesion. These minor differences are due to the specific grain size content of the tested samples, in particular for the clay fraction.

For the intact sample collected at the contact with the flysch bedrock (WP23), the lowest peak shear strength values were found to be $\phi'_p = 24.1°$ and $c'_p = 19.9$ kPa. These values were obtained from triaxial tests (TXCIU) under the same normal stress and rate of displacement used in direct shear tests. In general, the peak conditions for colluvial silty-clayey soils were reached for horizontal displacements of about 4–9 mm, highlighting a plastic behaviour of the hardening type.

In order to consider the prevailing coarse fraction of the granular fluidised sample (WP25), a bigger Casagrande square shear box (10 x 10 x 3 cm) was used, with a greater rate of displacement of 0.025 mm/min and a range of normal stress between 50 < σ_v < 150 kPa. In this case, the shear strength parameters were $\phi'_p = 35°$ and $c'_p = 3$ kPa.

For comparison purposes, two additional direct shear tests were performed on intact round samples (diameter of 60 mm) that were collected on the eastern scarp, using lower values of confining pressure (σ_v = 25–100 kPa). Values of the peak friction angle were 21.4° and 26.7°, whereas corresponding values of the peak cohesion were 29.8 kPa and 11.2 kPa. This difference may be due to the combined effect of the specimen shape and the lower confining pressure.

Some residual shear strength tests were performed in a Bromhead ring shear apparatus on reconstituted samples that only included the fine fraction (ASTM#40 sieve passing material) and with a water content greater than liquid limit. These tests were carried out in drained conditions and at a displacement rate of 0.032°/min.

For the colluvial soil sampled from the New Eastern Scarp sample (NES-2024 UD), the residual shear strength properties were ϕ'_r = 26.6° and c'_r = 3 kPa, associated with a plasticity index of *PI* = 22% and a clay fraction of CF* = 32%. No differences were found when compared with the peak friction angle of the samples in natural conditions, thus confirming the prevailing influence of the finer matrix on the overall shear resistance and a scarce importance of the soil structure.

The residual shear strength of colluvial materials was also investigated in the ICL-1 ring shear apparatus (Marui Company, Japan), in the undrained condition, under an effective normal stress of 50, 100 and 200 kPa and with a shear rate control of 0.01 cm/s. The residual cohesion determined was 6 kPa and the residual friction angle was 17° on the NES-2024 RI sample. Figure 6 shows an example of the ring shear test in undrained shear speed control test at an effective normal stress of 100 kPa.

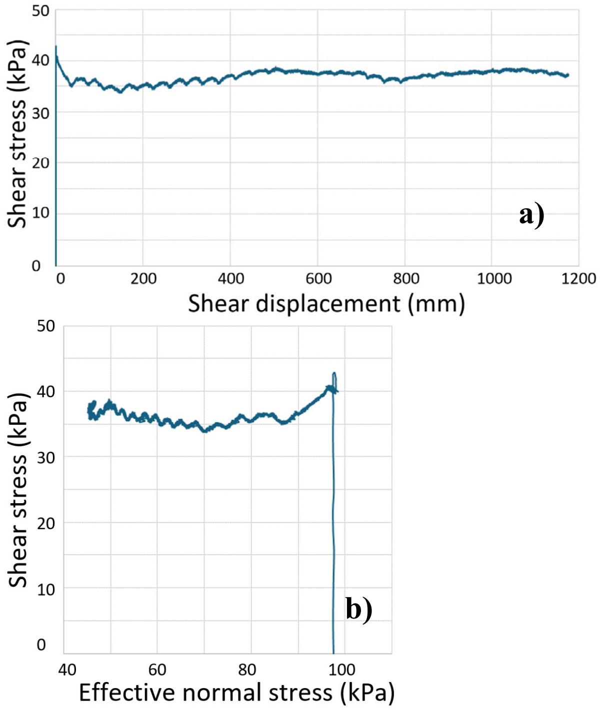

Figure 6. Ring shear test in undrained shear speed control test at 100 kPa of effective normal stress: a) shear stress–shear displacement diagram; and b) effective stress path.

4 DISCUSSION AND CONCLUSIONS

Thanks to the involvement of two independent Geotechnical Laboratories (Universities of Udine and Rijeka), the investigated geomechanical properties of the colluvial soils sampled from the Sedilis unstable slope can be compared. Main results of the tests from the two laboratories, which were related to samples collected from the New Eastern Scarp 2024, are summarised in Tables 2, 3 and 4.

According to the grain size analyses (Table 2), it was calculated that:

- the single prevailing soil fraction is associated with silt, which approximately represents 40% of the total;
- the clay fraction is about 25%;
- the fine fraction is prevalent and represents the two thirds of the total content;
- the coarse fraction is considerable and represents one third of the total.

Table 2. Comparison of grain size properties of the common samples collected from the New Eastern Scarp 2024 (UD = Udine and RI = Rijeka).

Parameter	Symbol	UD Values	RI Values	Percentage
Gravel	*Gr*	6.5	9.4	%
Sand	*Sa*	27.2	23.6	%
Silt	*Si*	38.4	42.1	%
Clay	*CF*	27.8	24.8	%
Gravel + Sand		33.7	33.0	%
Sand + Silt		65.7	65.8	%
Silt + Clay		66.3	67.0	%

The wide range in the values of index properties is strictly related to the intrinsic grain size variability of colluvial soils, which include a considerable content of rock fragments. The average values of index properties of colluvial materials sampled from the New Eastern Scarp 2024 are as follows (Table 3): e = 0.88, n = 0.47, w_n = 31%, S_R = 92%, θ_w = 0.44, γ_n = 18.6 kN/m³.

Table 3. Comparison of index properties of the common samples collected from the New Eastern Scarp 2024 (UD = Udine and RI = Rijeka).

Parameter		UD Values	RI Values	Unit
Void Index	e	0.78 –1.04	0.94	-
Porosity	n	0.44 – 0.51	0.48	-
Water content	w_n	25.5 – 36.9	29.2	%
Saturation degree	S_R	82 – 100	68	%
Volumetric WC	θ_W	0.37 – 0.51	0.33	-
Specific gravity	*Gs*	2.64 – 2.66	2.65	-
Bulk unit weight	γ_n	17.6 –20.1	16.96	kN/m³

The comparison of consistency and activity properties for the commonly investigated flysch-derived soils are reported in Table 4. The results show a good agreement and, as outlined for all Sedilis samples, colluvial soils are characterised by medium-to-low values of the plasticity and activity indexes. For the analysed samples, mean values of *PI* = 22% and *AI* = 0.77 were found, with a plastic consistency and the associated index value I_C = 0.60. AMI was less than 1.0 and this means that the soil in natural conditions needs to adsorb additional water to fluidise.

Table 4. Comparison of average consistency and activity properties of the common samples collected from the New Eastern Scarp 2024 (UD = Udine and RI = Rijeka).

Parameter		UD Values	RI Values
Liquid limit	w_L	43.5%	42%
Plastic limit	w_P	21.5%	20%
Plasticity Index	*PI*	22.0%	22%
Activity Index	*AI*	0.77	--
Consistency Index	I_C	0.60	0.58
Liquidity Index	I_L	0.40	0.42
Approx. Mobility Index	*AMI*	0.77	--

In addition, when considering other flysch-derived colluvial soils collected during the 20-25 surveys (except the fluidised sample WP25), they can be considered as matrix-supported loamy materials with a notable variability (Table 5). According to the grain size composition curves (Figure 3), the fine-grained soils can be mostly classified as clayey sandy silts characterised by medium-to-low values of consistency and plasticity properties, that is they can be classified as CL according to the Unified Soil Classification System. There are also cases of silt with clay of high plasticity (CH for sample C3 from the NWS2022) or coarse-grained soils (fluidised sample WP25), with completely different shear and hydraulic properties.

Table 5. Synthetised properties of fine colluvial soil samples.

Parameter		NWS2022 (C3-C8)	WP23	WP24-SW25
Liquid limit	W_L	49.4–53.1%	40.7%	37.5%
Plasticity Index	*PI*	25.0–29.7%	18.6%	13.9%
Passing ASTM#40	*#40*	72-99%	71%	68%
Passing ASTM#200	*#200*	64-97%	60%	57%

Overall, flysch-derived colluvial soils collected from the channelised landslide deposit pointed out the following average composition: 12% gravel, 23% sand, 39% silt, and 26% clay. The loamy matrix (Sand+Silt+Clay) was always prevailing (81–99%) on the coarse fraction, which is made up of gravel and rock fragments (1–19%).

When considering the different shear strength tests of the undisturbed natural samples from the Sedilis unstable slope, two range of characteristic values were identified. Peak shear strength properties of soils with a prevailing fine matrix and a scarce coarse fraction were characterized by reference values of the peak friction angle equal to $\phi'_p = 26–27°$ and cohesion of $c'_p = 3–16$ kPa. For colluvial soils with a prevailing coarse skeleton and a not negligible fine fraction, values of the peak friction angle increased up to $\phi'_p = 33–38°$, whereas the cohesion was $c'_p = 3–11$ kPa. When considering residual conditions, the friction angle decreased to the minimum values of $\phi'_r = 16°–17°$ for soils with a high clay fraction in the prevalent fine matrix and at greater depths, whereas decreased by up to 31°–33° for soils with a prevalent coarse soil skeleton.

The permeability of colluvial soils, measured both in-situ and in the laboratory, was characterised by a rather wide range, but some reference values can be differentiated in 10^{-6} m/s < K < 10^{-5} m/s for matrix-supported loamy materials and 10^{-5} m/s < K < 10^{-4} m/s for colluvial soils with a prevalent coarse soil skeleton.

The variability in both shear strength and permeability properties depends on the typical grain size heterogeneity of colluvial soils as well as on plasticity and water content of the fine fraction and on the specific position within the colluvial deposit. The reference values of hydraulic conductivity may change from about half to one order of magnitude, whereas reference values of the friction angle differ of only 10%.

The here-reported geotechnical parameters of flysch-derived colluvial materials pointed out their intrinsic heterogeneity and provide reference values useful to a comprehensive characterisation and/or classification, also suggesting the importance to consider spatial variability and uncertainty of the geotechnical and hydrological parameters. Consequently, when performing stability analyses of colluvial slopes affected by rainfall-induced landslides, it should not be employed a single value, rather than a range that takes into account the variability of flysch-derived colluvial materials.

5 ACKNOWLEDGEMENTS

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