PHYSICAL AND MECHANICAL CHARACTERIZATION OF THE SOFT PYROCLASTIC ROCKS FORMING THE ORVIETO CLIFF

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ABSTRACT

The paper describes the results of laboratory and in situ investigations carried out on weak pyroclastic materials which could be encountered during engineering activities in volcanic regions. The research was focused on the historical town of Orvieto, representing a typical geotechnical situation which is widespread in Central Italy. The in situ investigations include cross-hole and SASW measurements performed in adjacent areas. The laboratory tests provided static and dynamic properties which were compared to the in situ data, in order to reconstruct the geotechnical model of a representative area of the town.

1. INTRODUCTION

The products of the volcanic apparata located on the western margin of the Italian peninsula covered a large region north of Rome. The soft pyroclastic rocks forming most of the volcanic plateau allowed the erosion to carve out a typical landscape characterized by mesas and hinselbergs delimited by subvertical cliffs, where, on top, historical towns rise. At Orvieto, repeated instabilities on the tuffaceous cliffs and in the underground cavities excavated in the pyroclastic materials have conditioned the urban development and have threatened historical buildings, which were also damaged during strong earthquakes.

At the end of 70's, a research on the long-term stability mechanisms of the hill was undertaken (Manfredini et al. 1980, Lembo-Fazio et al. 1984, Tommasi et al. 1996). In particular this paper will focus on the geotechnical characterization of the pozzolana, which is weakest lithotype of the Orvieto slab. The investigation programme included in situ dynamic measurements and laboratory dynamic and static tests.

2. GEOLOGY OF THE INVESTIGATED AREA

2.1 The "Orvieto Tuff" formation

Orvieto extends over the top of an isolated rock slab, overlying a stiff clay substratum. The slab, delimited by subvertical cliffs up to 60 m high, is carved in the upper unit of the "Orvieto Tuff" formation, which consists of a lithic facies (tuff) and of a weakly lithified facies (pozzolana).

The genesis of the pyroclastic formation was ascribed by Nappi et al. (1994) to a gaseous-rich dry flow of the Vulsini Volcano, whilst Faraone & Stoppa (1988) recognized different

Figure 1. View of the investigation site at the edge of the southern cliff.

flows. The lower lithic tuff derived from a first wet flow; a second eruption produced a dry flow and a further condense-rich flow, which formed respectively the pozzolana and the upper lithic tuff. Observations on the cliff and in underground cavities, as well as borehole data, indicate that the passage from the lithic tuff to the pozzolana is quite irregular and often gradual. This could suggest that the two facies were also differentiated by other singenetic or secondary processes (e.g. zeolitization; Manfredini et al. 1980).

2.2 Stratigraphy and structural characters of the site

The zone where investigations were carried out is located at the southern margin of the slab. On the cliff face (Fig. 1), from bottom to top, a basal layer of lithic tuff a few meters thick is overlaid by the pozzolanic facies, which extends up to the cliff edge. The pozzolana can be subdivided into a lower competent layer and in a softer upper layer, which weakens at the top. At the bottom of the pozzolana, large pumices are abundant and progressively decrease proceeding upwards; they are stronger than the matrix and have a high relief on the cliff face.

The tuff is cut into prisms by vertical systematic joints which extend upwards into the competent pozzolana. The upper pozzolana layer is instead massive with rare irregular cracks (Fig. 1). The cliff is vertical from its foot up to the bottom of the lower pozzolana where it suddenly becomes less steep. A further decrease of the cliff slope can be observed in the weakest cap of the formation where the largest cavities were excavated.

The slab margin is affected by different instability phenomena largely dependent on the interaction between the slab and the clay substratum (Lembo Fazio et al. 1984). In the pozzolana, shear failures at the base of prisms and slices delimited by irregular tension fractures are frequent (Fig. 1). Failure also involves entire sectors of the cliff, producing large debris fans formed by irregular blocks in a loose, fine-grained, pumice-rich matrix.

At Orvieto more than 1000 cavities and quarries were excavated at different elevations (often superimposed). In the shallow cavities, roof failures are frequent, whereas in the pozzolana quarries located at intermediate and low levels, pillar collapses and sidewall spallings were observed.

3. MECHANICAL BEHAVIOUR AT FIELD SCALE

3.1 Cross-hole investigations

The cross-hole investigations were carried out through the entire pozzolanic sequence from 0 down to 36 m, between vertical boreholes having a distance of 3.6 m. Boreholes were located 15 m behind the cliff face (Fig. 1).

Waves were generated by means of a hammer and were acquired using 7 and 10 Hz geophones. Shots were 3 m and 1 m spaced for P- and S-wave respectively. In this paper, the results of V_P and V_S from direct wave measurements are reported (Fig. 2). A detailed description of measurement and processing procedures is reported by Cardarelli et al. (2002).

3.2 SASW investigations

Another dynamic technique applied here is the SASW (Spectral Analysis of Surface Wave) method (Nazarian 1984, Stokoe et al. 1988), which provides a profile with depth of the dynamic tangential modulus G. The SASW method is based on generating Rayleigh waves of a wide spectrum of frequencies by applying an impact on the surface. Interpretation requires a spectral analysis of acquired signals, followed by the resolution of a non-linear inverse problem, which is solved through an iterative procedure based on the comparison between an elaborated function and a theoretical solution derived for a layered elastic medium (Yuan & Nazarian 1993, Rix & Lai 2000). Successively S-wave velocity can be, as a good approximation, calculated from R-wave velocity by assuming a stuitable value of the Poisson ratio.

The SASW investigations were carried out in an ancient pozzolana quarry that extends perpendicularly to the cliff wall, 11 m below the surface and 50 m beside the cross-hole boreholes (Fig. 1). Only one vertical section was investigated; the alignment, 40 m long, is located at a minimum distance of some 25 m from the cliff edge.

Instrumentation includes a 50 N hammer and a 170 N falling mass, released from a height of 1.2 m, as the impact sources and two 50 kHz piezoelectric transducers connected to a digital storage oscilloscope (Rotonda 2001). As the geometrical configuration, the common receiver midpoint scheme was adopted. The distances between the transducers and the centerline were: 1.0, 2.0, 4.0, 6.0 and 8.9 m, and the distances between the impact source and the centerline were twice as much. For each distance, four measurements were made in order to average the received signals.

The S-wave velocity profile (a Poisson ratio equal to 0.30 was assumed) is shown in Figure 2. V_S gradually increases with depth within a 3 m thick layer and remains at a constant value of 620 m/s in the underlaying rock. The low stiffness of the shallow layer could be related to excavation disturbance and to the loosening of the floor. The investigated depth did not exceeded 7 m, owed to the poor elastic characteristics of the pozzolana; the difficult location of the alignment did not allow operating with impact sources to generate longer wavelengths.

In the Figure 2 the velocities from the cross-hole measurements are also reported. Apart from the shallow layer under the cavity floor, cross-hole velocities are slightly higher than those measured by the SASW technique. Differences could be ascribed to local non-homogeneity and to the greater distance of the SASW alignment from the cliff wall, which implies a less severe state of stress in the rock mass. For most practical applications these differences are small and were observed in other comparative studies of the two techniques (Nazarian 1984, Hiltunen & Woods 1988). Unfortunately the SASW measurements got to a maximum depth which does not include the lower competent layer.

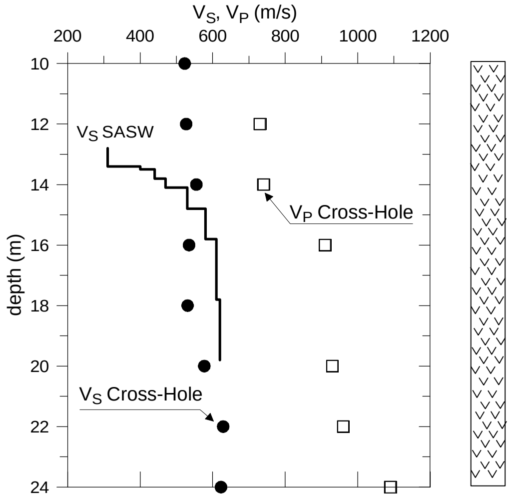


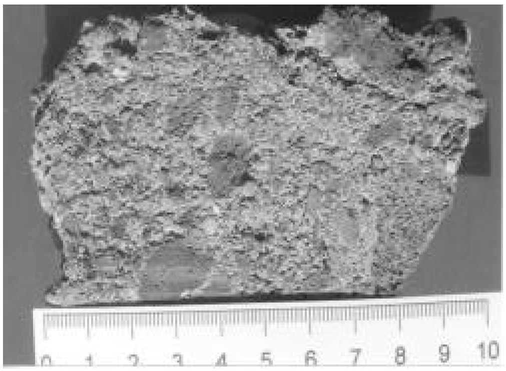
Figure 2. P- and S-wave velocities from the in situ investigations.

4. INVESTIGATIONS AT LABORATORY SCALE

4.1 Textural characters

At the specimen scale the pozzolana appears as being a glassy mass where clasts (pumices, lithic fragments and phenocristals) are immersed (Fig. 3). Lithic fragments do not exceed some 30 mm, whilst the pumice diameter ranges from 2-3 mm to several centimeters.

Analyses at the scanning electron and polarizing microscopes show that no separation can be observed between the clasts and the glassy mass. The mass looks like a multitude of microscopic, irregular volcanic glass lumps, which are in continuity with each other along a few areas distributed around their boundaries (Fig. 3). This highly three-dimensional scheme is also supported by the fact that, in a same thin section, continuity among the glass lumps is only found on superimposed focus planes. Such a texture determines high porosity (n = 52-59%) but seems to form a sort of frame. Zeolites are extremely rare in the pozzolana, whereas in the lithic tuff, they completely cover the pore walls (Tommasi & Ribacchi 1998).



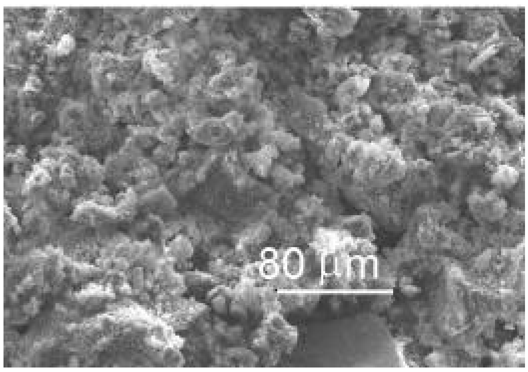


Figure 3. Sawed surface (left) and SEM picture of a fractured surface of pozzolana (right).

4.2 Sampling and specimen preparation

From cores recovered from the boreholes, cylindrical specimens 78 mm in diameter were obtained for mechanical testing.

The great difference in strength and cuttability between the pozzolana matrix and the stronger clasts resulted in an extremely difficult core recovering, sawing and grinding. Since strong irregularity of the lateral core surfaces could not be avoided, before sawing and grinding, samples were wrapped with a thick foil of deformable material and inserted in PVC tubes. The PVC improves the perpendicularity between specimen ends and axis, and prevents the detachments of clasts during the grinding/sawing operations. Specimen ends were regularized with plaster and successively grinded. Plaster coating was also used to regularize the two opposite loading strips of specimens for Brazil testing.

Most of the mechanical tests were carried out on specimens of the competent pozzolana. In this material, longer cores were in fact drilled, due to the lower strength contrast between the matrix and the clasts.

4.3 Physical and mechanical properties

Physical properties of the pozzolana are summarized in Table 1 together with values determined on the lithic tuff. In spite of a similar dry density r_d, pozzolana is more porous than tuff; in fact the absence of zeolites increases the grain density r_s. The lower pozzolana is characterized by a significant reduction of the porosity, which is necessarily related to a reduction of the glassy mass pores, since large pumices are more abundant and extremely porous.

Table 1. Physical properties of the pyroclastic materials.

Lithotype	ρ_d (Mg/m^3)			ρ_s (Mg/m^3)			Porosity n (%)		
	Av.	σ	N	Av.	σ	N	Av.	σ	N
Weak pozzolana	1.06	0.037	19	2.62	0.013	9	59.7	1.4	19
Competent pozzolana	1.15	0.046	31	2.62	-	4	56.1	1.8	31
Tuff, red facies	1.18	0.035	47	2.34	-	3	49.5	1.5	47
Tuff, yellow facies	1.09	0.040	32	2.31	-	3	52.8	1.9	32

On specimens oven-dried at 40 °C, uniaxial and Brazil tests were performed with a constant displacement-rate loading machine. Axial strains were measured by means of displacement transducers, which were clamped onto the lateral surface.

Mechanical parameters are summarized in Table 2, where a comparison with the tuff values is again provided. In uniaxial compression, the material exhibits a brittle behaviour (Fig. 4). The maximum stiffness is always reached within a very short stress range, close to 50% of the uniaxial strength σ_f (i.e. E_{t50}), and it is followed by a symmetrical gradual decrease. The high dispersion and the poor correlation with porosity of the tensile strength σ_t can be due to the departure of the failure surface from the axial plane induced by clasts.

Table 2. Mechanical properties of the pyroclastic materials.

Lithotype	σ_f (MPa)			σ_t (kPa)			E_{t50} (MPa)		
	Av.	σ	N	Av.	σ	N	Av.	σ	N
Weak pozzolana	0.90	-	2	66	20	9	430	-	2
Competent pozzolana	2.28	0.51	17	92	-	3	1110	390	17
Tuff, red facies	4.52	0.98	36	640	103	26	2290	470	13
Tuff, yellow facies	3.00	0.80	18	560	110	16	1380	223	6

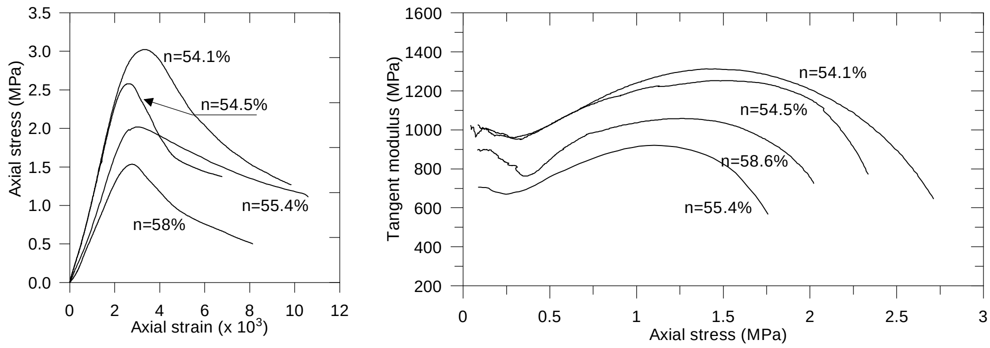


Figure. 4. Typical stress-strain curves (left); plots of tangent modulus versus axial stress (right).

4.4 Dynamic behaviour

Ultrasonic velocities of longitudinal and shear waves were determined on cylindrical specimens by measuring the transit time of a square wave. The impulse was generated by a Pundit pulser through Panametrics piezoelectric transducers, having a typical frequency of 1 MHz. Transducers were coupled to the ends of the specimens by means of a slight load (0.2 kN) and by spreading of an acoustic couplant between the transducer and a sheet of aluminium. The transit time within the plaster caps was properly subtracted from the total measured time.

On the 41 specimens prepared for the mechanical tests, P- and S-wave velocities were determined in perfectly dry conditions; for the whole set of specimens mean values of 1382 and 685 m/s were obtained for V_P and V_S respectively.

In Figure 5 wave velocities, together with dry density, are plotted versus the sampling depth. The log values rebate the lithologic differences observed in situ and in the borehole cores. The shallow weak layer and the competent layer with large pumices are associated to significant velocity changes. The sharp velocity increase at the log bottom could be partially due to the abundance of pumices, whose velocities are particularly high ($V_P \approx 2500$ m/s).

An almost linear trend between both velocities and porosity is observed; a similar linear variation was detected by the authors from other pozzolana and tuff samples from Orvieto and in other volcanic formations.

Measurements of the P-wave velocity were carried out also in different saturation conditions. From partially saturated to dry conditions, the P-wave velocity was determined on three borehole specimens and on a single specimen taken in the cavity at natural water content. Water loss produces a robust increase in the P-wave velocity, but the product of the density with the squared velocity does not show a significant variation, thus evidencing that elastic moduli could not be greatly influenced by the partial saturation. The saturation degree determined at the ambient conditions of the cavity was 0.34.

5. DYNAMIC ELASTIC MODULI AT DIFFERENT SCALES

The velocities from the laboratory (dry conditions) and from the field are plotted versus depth in Figure 5. In comparing the velocities, the influence of water content has to be considered; at in situ conditions, since groundwater is below the pyroclastic slab, only free porosity can be water filled, so that the rock mass behaves as if the voids were saturated by a air-water fluid having very high compressibility. The in situ velocities could be related to the dry moduli and the presence of water only influences bulk density.

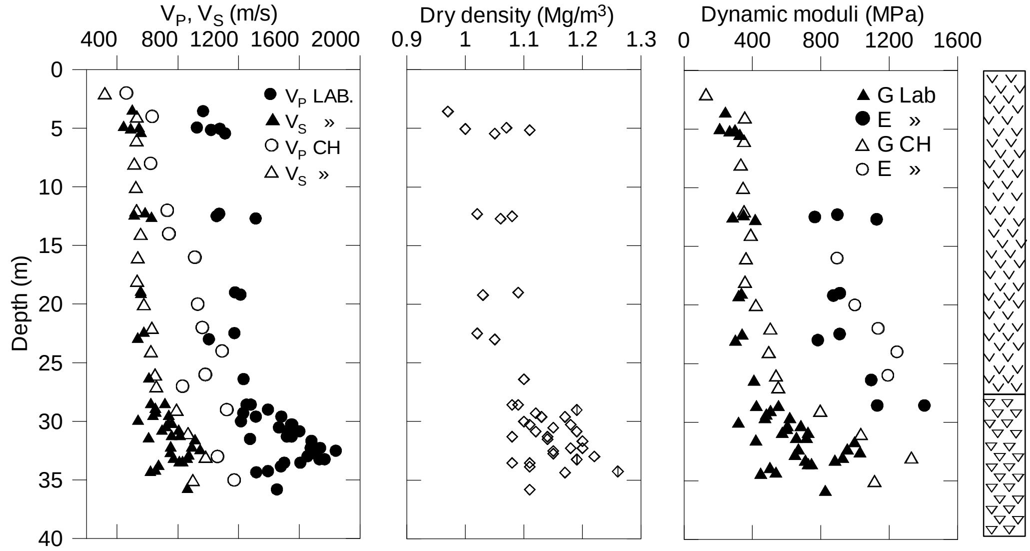


Figure. 5. P- and S-wave velocities from laboratory and in situ investigations (left); elastic dynamic moduli from laboratory and in situ investigations (right)

In this hypothesis Young and shear dynamic moduli were calculated from both in situ and laboratory velocities (an estimated value of the in situ density which accounts for the natural water content was adopted) (Fig. 5). The comparison evidences that a good correlation between the moduli at the different scales exists; the greater difference is found in the lower more competent layer, where the presence of larger pumices introduces a marked scale effect.

These results also indicate that the stiffness of the pozzolana at the investigated scale is not influenced by discontinuities, because the rock mass has a massive structure and discontinuities are largely spaced.

6. CONCLUDING REMARKS

The pozzolana is characterized by poor mechanical properties; for example, the very low tensile strength is comparable to the horizontal stress (calculated by means of numerical models) acting at the slab margin, which is responsible for the widespread tension cracks.

However static and dynamic tests confirm that the material owns a certain small- and large-scale stiffness which is due to its particular texture. Lithology is largely variable, depending both on the continuity of the glassy mass and on the abundance and size of the clasts (i.e. pumices). Even though laboratory tests mainly reflect the mechanical behaviour of the glassy mass and subordinately of the largest pumices, they revealed to be virtually representative of the in situ dynamic behaviour. This result indicates that laboratory tests can be effective in providing elastic moduli profiles to be used for many engineering applications (e.g. seismic response analyses) in such a weak rock, especially when borehole geophysics is expensive or technically difficult (e.g. relatively deep or sub-horizontal surveys). In fact large-scale stiffness reduction due to discontinuities can be excluded because the deposit is characterized by a massive structure with rare tension fractures. Only a moderate increase of in situ stiffness was observed; it could be ascribed to the higher stiffness of the large pumices and to the actual in situ state of stress.

On such a high porosity rock, differences in the saturation degree (markedly lower than one) does not influence dynamic stiffness but results in a change of in situ wave velocities only due to the variation of bulk density.

The SASW method revealed to be applicable to weak pyroclastic materials and confirmed to be satisfactorily correlated to cross-hole data; a strong energization is however required if a significant depth is to be investigated.

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