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Review article
"Remarks on factors influencing shear wave velocities and their role in evaluating susceptibilities to earthquake-triggered slope instability: case study for the Campania area (Italy)"

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Abstract. Shear wave velocities have a fundamental role in connection with the mitigation of seismic hazards, as their low values are the main causes of site amplification phenomena and can significantly influence the susceptibility of a territory to seismic-induced landslides. The shear wave velocity (Vs) and modulus (*G*) of each lithological unit are influenced by factors such as the degree of fracturing and faulting, the porosity, the clay amount and the precipitation, with the latter two influencing the unit water content. In this paper we discuss how these factors can affect the Vs values and report the results of different analyses that quantify the reduction in the rock Vs and shear modulus values connected to the presence of clay and water. We also show that significant results in assessing seismic-induced slope failure susceptibility for land planning targets could be achieved through a careful evaluation, based only on literature studies, of the geo-lithological and geo-seismic features of the study area.

1 Introduction

A crucial aspect in seismic hazard evaluation for land planning targets is the estimation of the territory's susceptibility to earthquake-triggered landslides, which represent one of the major natural hazards in landslide-prone seismic areas (e.g. Jibson et al., 2000; Wick et al., 2010). A comprehensive approach to guide land planning in connection with mitigation of seismic hazard (e.g. Nath and Thingbaijam, 2009) should not only refer to local soil amplification phenomena but also involve a careful assessment of the slope stability. The effect of seismically-induced landslides on human lives and facilities may in fact even exceed the damage directly connected to the shaking.

Several investigations have been carried out with the aim of defining procedures for a detailed study of the seismic hazard of a specific site of small extension with regard to seismic-induced landslides (scale range 1:5000–1:1000) (e.g. ISSMGE-TC4, 1999). These methods need precise measures of several parameters and make use of complex numerical methodologies. This necessarily leads to high costs for each investigated site. On the other hand, land planning studies are generally carried out at larger scales (scale range 1:25 000–1:10 000) and a detailed analysis would therefore be inappropriate for the sought target, as far as cost and time are concerned. In fact, land use planning needs information about seismic hazard at a sustainable cost, whereas more complete, detailed and expensive studies should be focused only on areas where a detailed zoning is necessary.

Rapolla et al. (2010, 2012) proposed a quick strategy for land planning targets which employs the shear wave velocity values (Vs) as crucial factor for zoning on seismic-induced landslide susceptibility. The method, whose approach is shared by other procedures (e.g. Miles and Keefer, 2007), needs a careful evaluation of the unit's geomechanical and geophysical features, which could be possibly based on literature studies only. Shear wave velocity and modulus are strongly influenced by factors such as porosity, clay content and precipitation, which control the water content. Knowing how these factors affect the Vs values of each lithological unit and, as a consequence, its response to a seismic input is thus a key issue. In this paper we shall discuss the main factors influencing shear wave velocities and modulus and briefly describe some aspects of the above cited zoning strategy – with emphasis on role for Vs in evaluating seismic-induced slope failure susceptibility.

2 Remarks on the role for Vs values in seismic hazard

Several studies (e.g. Riepl et al., 2000; Louie, 2001; Wang and Hao, 2002; Thompson et al., 2010; Theilen-Willige, 2010) showed the fundamental role of Vs in connection with seismic hazard. Site amplification phenomena can be as high as several times the incoming wave amplitude, depending on the incoming wave properties and site geo-seismic characteristics. Local conditions, such as the presence of thick clay layers in the shallower geological units (e.g. İnce, 2011), are causes of low Vs values and are recognized to be the cause of a site's seismic action modifications, concerning the frequency content (referred to as "spectrum") and the peak intensity's amplification. In landslide-prone regions, a further seismic site amplification induced by topographic irregularities should be considered (e.g. Paolucci, 2002; Wald and Allen, 2007; Di Fiore, 2010).

The Vs values are strongly dependent on the seasonal climatic variations, as the presence of rainwater may significantly change the mechanical properties of rocks and soils – particularly in the case of clayey materials. This may result in a decrease of their shear modulus and, in non-flat areas, of slope strength. A careful evaluation of the slope geotechnical and geophysical features should thus be done so to account for the main variation factors that may affect the elastic moduli and, as a consequence, the shear wave velocities. In the following section, we discuss how factors such as the formation fracturing and porosity and the clay and water contents may affect the Vs values of rocks.

3 Factors influencing seismic velocities and elastic moduli

As known, slope stability is influenced by the balance between the resistance of materials to the motion and the action of external forces (gravity and earthquakes). The specific behaviour of a particular lithotype, i.e. its response to stress, depends on the stress/strain relations that characterize the examined lithotype, which in turns depends on its elastic moduli and density. The most important factors of influence on the elastic moduli, and consequently on the velocity of seismic waves of a material, are its compactness, porosity, degree of fracturing and weathering, mineralogical composition (which influences its clay content), water content, and its depth and age. All these characteristics control the litho-seismic and geomechanical behaviour of the materials and consequently affect both seismic site amplifications and resistance of slopes to the shaking connected to earthquakes. As the literature studies described below refer to rock samples, we note that in presence of joints, fault planes and slipping surfaces, a lower slope's mechanical characteristics (shear resistance, cohesion) may be expected. Moreover, rock shear wave variations depend also on the scale of observations, with the reduction in clay shear resistance connected to the presence of smear joints and/or to fault planes being only reflected when observed at a detailed scale.

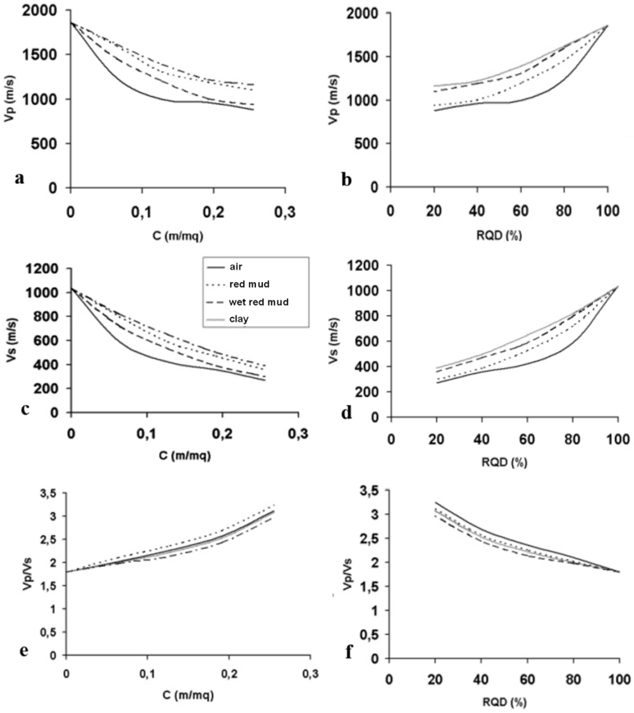

Fig. 1. Plots of **(a)** Vp versus density of fracturing C, **(b)** Vp versus quality factor RQD, **(c)** Vs versus density of fracturing C, **(d)** Vs versus quality factor RQD, **(e)** ratio Vp/Vs versus density of fracturing C, **(f)** ratio Vp/Vs versus quality factor RQD. Note that y-axes are not in scale. Modified after Leucci and De Giorgi (2003).

3.1 Degree of fracturing

Several authors (e.g. Gaviglio, 1989; Watanabe and Sassa, 1995; Kahraman, 2002) dealt with the study of propagation velocity of longitudinal waves in fractured rocks, as they are more easily detectable than transversal waves. Boadu and Long (1996) proposed a model of fracture called MDD (*Modified Displacement Discontinuity*) to study the propagation of both types of seismic waves (P and S) in fractured media. Laboratory studies based on this model (Leucci and De Giorgi, 2003) established empirical relationships between parameters related to the degree of fracturing of a rock formation and the propagation velocity of both P and S waves. The experiments were conducted on samples of limestone containing artificial fractures, by gradually increasing the fracturing density and filling them with mud, wet mud and clay. The outcome shows that the increased density of fracturing C leads to a decrease in both the P and S waves

Table 1. Hard rock classification based on the quality factor RQD (modified after Leucci and De Giorgi, 2003).

RQD (%)	Rock quality
0–25	Very Poor
25–50	Poor
50–75	Fairly Good
75–90	Good
90–100	Excellent

velocity (Fig. 1a and c), and to a simultaneous increase in the ratio Vp/Vs between compressional and shear wave velocities (Fig. 1e). This last piece of evidence shows that the velocity of P waves is affected to a lesser extent by the increase in fracturing compared to the S wave velocity.

The increase in the density of fracturing causes a decrease in the quality factor of the rock RQD (*Rock Quality Designation*) (Boadu, 1997) (Table 1), which is a good indicator of rock quality for hard rocks. It is defined as the ratio of the sum of the distances between each fracture along a profile and the length of the profile itself. By plotting the rock quality factor RQD versus the velocity of seismic waves, the authors show how an increase in this factor is connected to an increase of P wave (Fig. 1b) and S wave (Fig. 1d) velocities and to a simultaneous reduction in the ratio Vp/Vs (Fig. 1f).

3.2 Porosity and clay content

Other important factors influencing seismic waves velocity are, as mentioned, the porosity, the presence of clay and the water content. Wyllie et al. (1956) determined an empirical relationship between the compression wave velocity and porosity for saturated samples having homogeneous mineralogical composition:

$$(1/V) = (1/V_{\mathrm{w}}) + [(1-\Phi)/V_{\mathrm{m}})] \qquad (1)$$

where V is the velocity of the rock, V_{w} is the velocity of the fluid that impregnates its pores, V_{m} is the matrix velocity, all expressed in $\mathrm{m\,s^{-1}}$, and Φ is the porosity. Equation (1), known as "Equation of Wyllie", shows a decrease in velocity in connection with an increase of porosity and is valid for non-clayey and normally consolidated formations with intergranular porosity, and when the saturation degree does not weaken the rock.

The latter is a very important aspect since, as shown later, in presence of clay the saturation degree has a high influence on the rock behaviour. A correct application of the Eq. (1) is limited to the case of pores and granules arranged in homogeneous layers perpendicular to the path of seismic beams and for average porosities ($10\,\% < \Phi < 25\,\%$) of clean sandstones. However, it is well known that there are several other factors influencing the velocity of seismic waves, such as the mineral composition, the pore geometry, the degree of cementation and consolidation, the confining pressure, the pore pressure and the temperature (Han et al., 1986). Therefore, the validity conditions of the equation of Wyllie are not likely to occur very often.

An integration with the empirical equation of Wyllie has been suggested by Raymer et al. (1980) and made it possible to correlate the compressional wave velocity with porosity for values of porosity higher than 25 %. The authors identified two separate porosity domains: the "suspension domain", for high-porosity rocks, describes a medium where solid particles are suspended in the fluid; the "consolidated rock domain", for rocks with low porosity, describes a medium with a continuous frame-supported matrix. Nur et al. (1998) defined the transition from one domain to the others as the "critical porosity". For porosities greater than the critical porosity, seismic velocities do not depend strongly on porosity. For porosities below the critical point, seismic velocities depend instead strongly on porosity and increase significantly for slight reductions in porosity.

Conversely to what is assumed by the equation of Wyllie et al. (1956), which is valid only for homogeneous formations not containing clay minerals and with low porosity, several subsequent studies have shown the essential influence of the presence of clay on the elastic moduli and velocities of seismic waves. The clay fraction appears in the form of particles precipitated on the walls of the matrix pores. Those clay particles create a micro-porosity made of pores smaller than 1 µm, which increases the porosity of the medium and greatly influences the velocity of seismic waves, decreasing it (e.g. Kowallis et al., 1984; Tosaya and Nur, 1982; Han et al., 1986, Goldberg and Gurevich, 1998; Klimentos and McCann, 1990).

Thus, more recent studies have included the porosity of the clay fraction in the empirical relationships to predict rock seismic velocities. In Table 2 we resume the results of some of those studies. Table 2a shows different equations from Tosaya and Nur (1982), Han et al. (1986) and Klimentos (1991) relating seismic velocities in $\mathrm{km\,s^{-1}}$ with volume fraction of clay C, volume fraction of pores Φ and, in one case, permeability K in saturated silty sandstones with a confining pressure $P_{\mathrm{c}} = 40\,\mathrm{MPa}$ (equivalent to a depth of about 1.5 km). The equations show that, even though velocity values depend more on porosity than on clay content (with the effect of porosity being at least twice that of the clay content), the latter decreases velocities as well. The equation found by Klimentos (1991) includes also the effect of permeability. Nevertheless, this effect was found to be negligible in rocks with identical porosity, lithology and similar clay content. We add that, for poorly consolidated sandstones at 10 MPa confining pressure, Kowallis et al. (1984) showed dry velocity data with linear trends of decreasing velocity with increasing porosity similar to those obtained by Tosaya and Nur (1982) for saturated sandstones at 40 MPa. A correlation between compressional and shear wave velocities can be obtained from the equations shown in Table 2b proposed by Castagna et al. (1985) and Han et al. (1986).

Table 2. Summary of some literature studies on correlations between seismic wave velocities (V_p–V_S) and their main influencing factors.

(A): Correlation Velocities (km s^{-1}) – Porosity Φ– Clay Content *C*– Permeability K		
Tosaya and Nur (1982) $V_P = 5.8–8.6\,\Phi–2.4\,C$	Han et al. (1986) $V_P = 5.59–6.93\,\Phi–2.18\,C$ $V_S = 3.52–4.91\,\Phi–1.89\,C$	Klimentos (1991) $V_P = 5.66–6.11\,\Phi–3.53\,C + 0.0007\,\mathrm{K}$
(B): Correlation between Compressional and Shear Wave Velocities		
Castagna et al. (1985) $V_\mathrm{p} = 1.16\,V_\mathrm{s} + 1.36$	Han et al. (1986) $V_\mathrm{p} = 1.26\,V_\mathrm{s} + 1.07$	

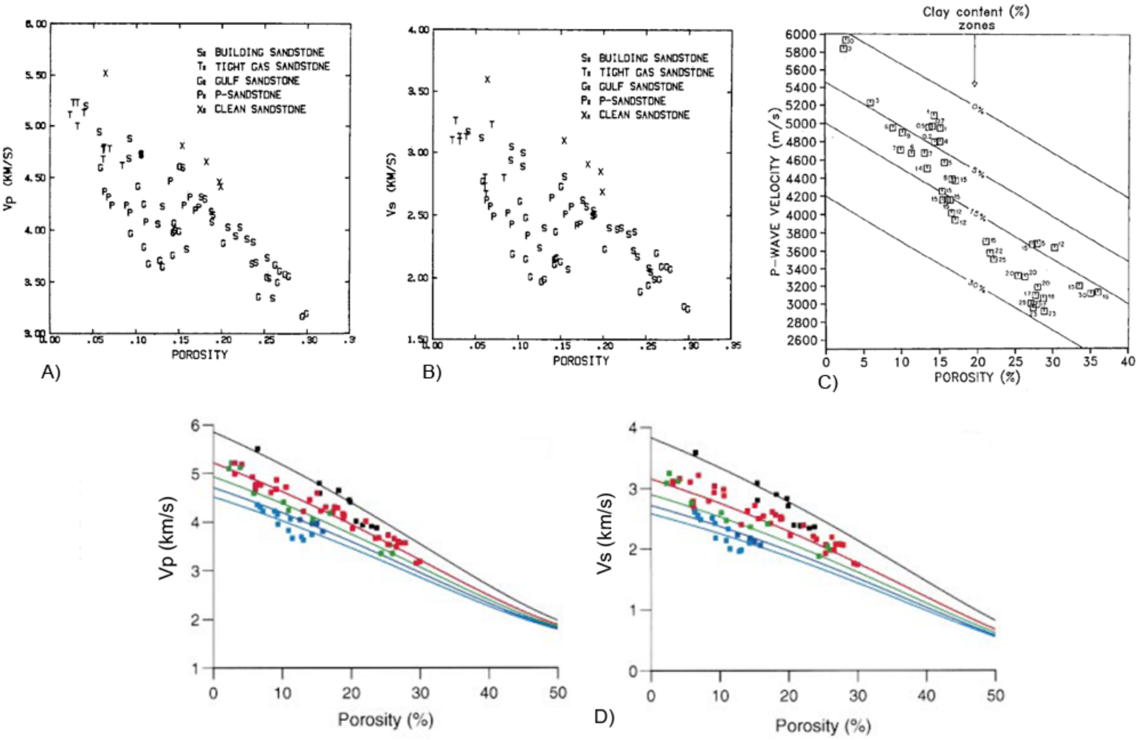

Fig. 2. Plots summarizing some literature studies on seismic velocities versus porosity. Modified after Han et al. (1986) (plots **A–B**), Klimentos (1991) (plot **C**) and Carcione et al. (2000) (plot **D**).

Some of the results of the study conducted by Han et al. (1986) are shown in the plots of Fig. 2a and b. Despite some data scatter due to the different chemical compositions of the samples, we note how both Vp and Vs decrease with increasing porosity and also how those velocities in non-shaly sandstones ("clean sandstone") are always considerably higher with respect to what are reported for shaly sandstones with the same porosity. The authors show how even a small amount of clay (volume fraction of 1–2 %) can significantly reduce velocities: the clay particles are arranged as lamina in the rocks or as grains between the sand grains and cause a softening of the sandstone matrix. The authors note also that seismic wave velocities are linearly related to porosity in the range 2–30 % and to clay content in the range 1–50 % and that the effect of clay in reducing wave velocities is about 1/3.2 as great of the effect of porosity for Vp and 1/2.6 times as great of the effect of porosity for Vs. Finally, the effects of porosity and clay content are larger on S waves than on P waves. Therefore, a sample with high porosity and clay content will tend to have a high Vp/Vs ratio. This effect was also observed by Blangy et al. (1993), who showed that dry ratios of Vp/Vs increase with porosity and clay content. In Fig. 2c we show also a plot of the result of the study performed by Klimentos (1991). The author confirms that the velocity of longitudinal waves decreases with increasing porosity and shows how, for a constant porosity, velocity decreases with increasing clay content, even though with some data scatter.

Carcione et al. (2000) (Fig. 2d) analyzed the characteristics of sandstones rich in clay through a tri-phase model

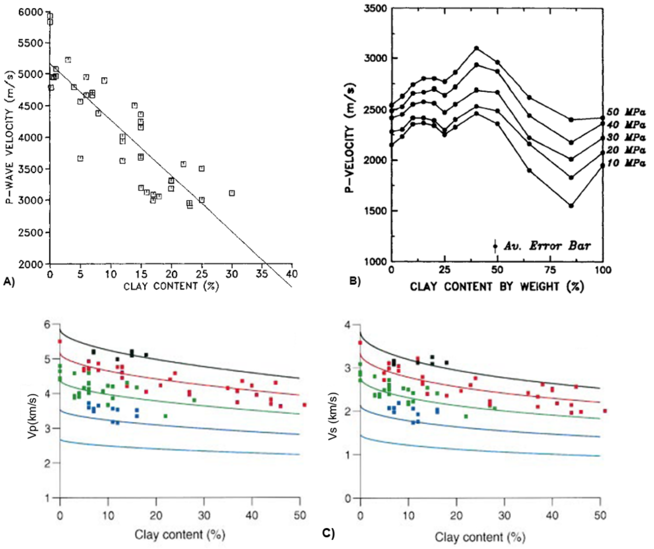

Fig. 3. Plots summarizing some literature studies on seismic velocities versus clay content. Modified after Klimentos (1991) (plot **A**), Marion et al. (1992) (plot **B**) and Carcione et al. (2000) (plot **C**).

consisting of fluid and two solid continuous matrices made of sand and clay particles and calibrated their analysis on the experimental data collected by Han et al. (1986) (represented in the plot by dots). The results of their study show again a decreasing trend of P and S wave velocities with increasing porosity, for different values of clay content: 0 % (black), 10 % (red), 20 % (green), 30 % (blue), 40 % (light blue).

In Fig. 3 we show the plots of velocities versus clay content obtained by different authors. Following the analysis by Klimentos (1991) (Fig. 3a), the decrease in P-wave velocity associated with increasing clay-content is connected to the increase of non-compressible clay micro-porosity or to the influence of the elastic moduli of the clay content itself.

Figure 3b reports the results of the study conducted by Marion et al. (1992) on unconsolidated brine saturated clean sands, pure kaolinite, and their mixtures at various confining pressures. The authors used a micro-geometrical model for mixtures of sand and clay in which two classes of sediments are considered: (1) sands and shaly sands, with clay volume fraction C smaller than sand porosity Φ_S, in which clay is dispersed in the pore space of sand and thus reduces porosity while increasing the elastic moduli of the pore-filling material and (2) shales and sandy shales, with clay volume fraction C higher than sand porosity Φ_S, in which sand grains are dispersed in a clay matrix. In this last case, porosity increases and elastic moduli decrease with increasing clay content. By considering the above described model, the authors found a peak in P velocity versus clay content in unconsolidated sand-clay mixtures at 40 percent clay by weight. The peak in velocity is 20–30 % higher than for either pure clay or clean sand.

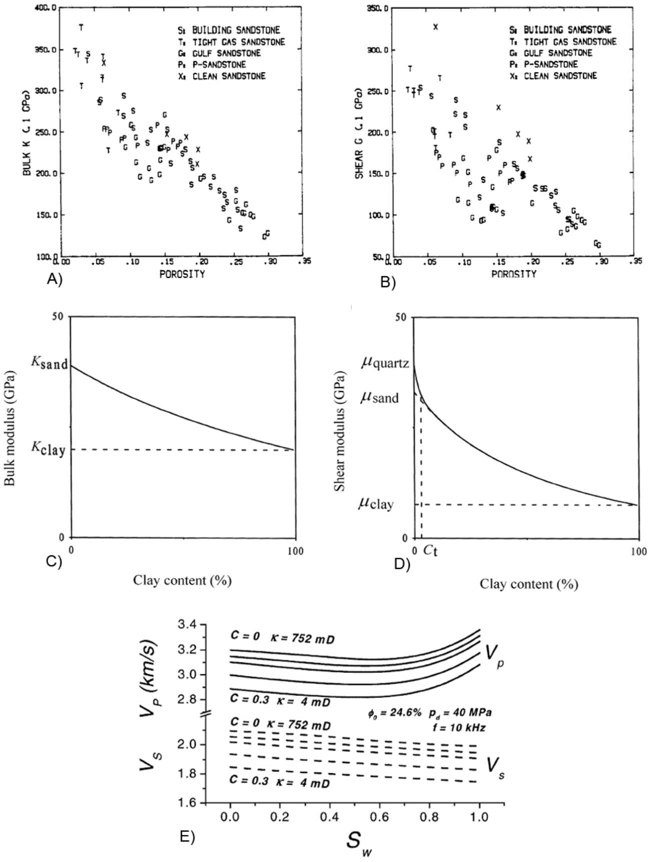

Fig. 4. Plots summarizing some literature studies on elastic moduli versus porosity and clay content. Modified after Han et al. (1986) (plots **A–B**), Golberg and Gurevich (1998) (plots **C–D**) and Pham et al. (2002) (plot **E**).

The plot of velocities vs. clay content obtained by Carcione et al. (2000) (Fig. 3c) shows an abrupt change of rock matrix properties with the addition of a very small amount of clay, attributed to softening of cements, clay swelling and surface effects, i.e. the wave velocities decrease significantly when the clay content increases from 0 to a few per cent. The colours in the plot refer to different values of porosity: 0 % (black), 10 % (red), 20 % (green), 30 % (blue), 40 % (light blue).

Regarding the effect of porosity and clay content on bulk and shear moduli, the plots of Fig. 4a and b show a decrease of the moduli with increasing either porosity or clay content. The plots obtained by Han et al. (1986) refer to the same samples and conditions as in Fig. 2a and b. They show that the sample mineralogical composition (presence of clay) has a greater influence on the pattern of the shear modulus vs. porosity than on the pattern of the bulk modulus vs. porosity.

Goldberg and Gurevich (1998) proposed a semi-empirical model of velocity-porosity-clay content for shaly sandstones. It employs a two-phase model consisting of fluid and a solid matrix made of sand and clay particles homogeneously

Table 3. Rock and soil classification based on geo-lithological, geomechanical and geophysical features (modified after Rapolla et al., 2010).

Geo-Lithological Characteristics:	Geomechanical Parameters		Geophysical Parameter
– Ground Type (OPCM, 2003; Eurocode 8, 2003) – Internal Disruption Level – Natural Humidity	N_{SPT}	C_{u}(kPa)	Vs (km s^{-1}) (average value)
Ground Type A			
(1) Coherent, non-fractured materials			>1.5
(2) Coherent, slightly fractured materials			1.5–0.8 (1.15)
Ground Type B			
Coherent, strongly fractured materials; deposits of stiff soil	>50	>250	0.8–0.36 (0.58)
Ground Type C			
Deposits of dense or medium-dense soil	15–50	250–70	0.36–0.18 (0.27)
Ground Type D			
Deposits of cohesionless soil	<15	<70	<0.18
Pseudo-coherent (clayey) materials			
(1) Low natural humidity		>50	>0.18
(2) High natural humidity		<50	<0.18

mixed to form composite granules. In order to use this model for clay-rich rocks, the authors assumed that the bulk and shear moduli of the grain material, and the dependence of the compliance on porosity, are function of the clay content. In agreement with what shown by Han et al. (1986) and reported by Carcione (2000), the authors observed an abrupt change in the rock matrix properties with the addition of small amounts of clay to a clean rock. Both Vp and Vs drop significantly when the clay content increases from 0 to the first few percentages. The authors observed that this phenomenon is mainly related to a reduction of the shear modulus, while the bulk modulus has a minor influence on velocity values (Fig. 4c–d). According to Han et al. (1986) and Klimentos (1991), such rapid changes of sandstone properties at very low clay content are a common feature of sandstones.

Figure 4e reports the results of the analysis from Pham et al. (2002), who continued the study of Carcione et al. (2000) and presented a tri-phase model for silty sandstones for predicting seismic wave velocities with varying conditions of saturation, content of clay and permeabilities. The authors showed that for 10 MHz and a porosity of about 24 %, an increase of the saturation causes an initial Vp decrease and then a Vp increase (at high saturations), along with a continuous decrease in Vs. Both types of wave velocities decrease as the clay content increases.

The above-mentioned studies summarized in Figs. 2, 3 and 4 converge in showing that the shear modulus and the velocity of seismic waves, and in particular of Vs, are strongly influenced by clay content and degree of saturation of the medium, which in turn is influenced by rainfall. These effects can be quantified as follows: for a constant porosity and water saturation, an increasing amount of clay from 0 % to about 30 % may cause a reduction of about 12 % in the Vs and of about 50 % in the shear modulus values, whereas for a constant porosity and clay content, an increasing saturation degree from 0 % to 100 % may lead to a reduction of 5–6 % in the Vs values.

4 Evaluating the geo-lithological properties for seismic-induced landslide zonation

In this Section we show how a careful evaluation of the above-reported geo-lithological properties may lead to meaningful zonation on seismic hazards, with emphasis of seismic-induced landslides. Rapolla et al. (2010, 2012) proposed a quick procedure to assess the seismic slope stability at different scales/levels that accounts for (A) the seismic-relevant property of the rocks/soils that crop out – expressed as transversal seismic velocity (Vs), (B) the incline angle of slopes – obtained from high-resolution digital elevation models of the topography of the investigated areas, (C) the seismic intensity that most likely will affect the study area – expressed in terms of European Macroseismic Scale (EMS-98), which is based on the the Mercalli-Cancani-Sieberg (MCS) and Medvedev-Sponheuer-Karnik (MSK-64) scales.

The seismically-induced landslide susceptibility level of an area can be obtained from the average of factors A and B, considered as *predisposing factor*, multiplied by the triggering factor C. Referring to the above cited literature for details about the procedure, we would like to note here that a crucial point of the procedure is a correct evaluation of the A parameter, the *lithology index*.

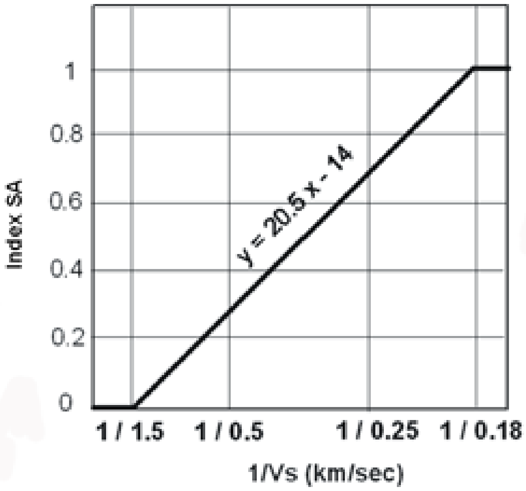

Fig. 5. Correlation between Vs values and *lithology index*. Modified after Rapolla et al. (2012).

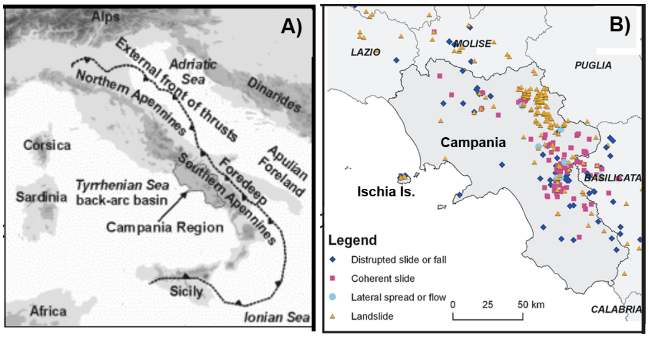

Fig. 6. Location of the Campania region within the Italian territory **(A)** and of the Ischia Island. **(B)** The seismic-induced landslides considered in the analysis are shown in plot **(B)**. Modified after Rapolla et al. (2012).

As far as the technical characteristics and the response to a mechanical action are concerned, rocks and soils can be classified in different ways, according to various qualitative/quantitative criteria. Following the same rock and soil classifications reported by the OPCM (2003) and Eurocode 8 (2003), based on three different criteria (geo-lithological, geomechanical and geophysical), it is possible to classify the outcropping soils and rocks on the basis of what is reported in Table 3. The above cited regulations regard transversal wave velocity as the most suitable parameter for evaluating the response of materials to the seismic action and introduce ground types. Ground types are classified on the basis of stratigraphic profiles and parameters, which can be used to account for the influence of local ground conditions on the seismic action. They include $V_{\mathrm{s},30}$ (km s^{-1}) (average value of propagation velocity of S waves in the upper 30 m of the soil profile), or as a second choice, N_{SPT} (blows/30 cm) (standard penetration test blow-count) and Cu (kpa) (undrained shear strength of soil).

Besides the ground types reported by the above cited seismic regulations, Table 3 accounts for further two types, i.e. coherent materials with Vs > 1.5 km s^{-1} and clayey soils whose geomechanical and seismic behaviour is strongly influenced by their natural humidity.

The average transversal wave velocity value (Vs) of each lithological unit should be evaluated with reference to the shallower portions of rocks and soils that are usually involved in seismic amplifications and/or in landslide phenomena. Through this evaluation, which may be carried out on the basis of both experimental data and/or data reported in literature, it is possible to refer to the units to the ground types of the Eurocode 8 (2003) classification (Table 3) and to estimate their *lithology index* through the inverse proportionality shown in Fig. 5. The index – in terms of landslide susceptibility – is assumed to be zero for rocks having Vs higher than 1.5 km s^{-1}, i.e. hard, non-fractured rocks and reaches a value of 1 for deposits having Vs lower than 0.18 km s^{-1}, i.e. cohesionless soils or pseudo-coherent (clayey) materials with high natural-humidity.

As far as the other parameters (B and C), the *slope* ,and *intensity indexes* are concerned, the authors assumed a direct proportionality between the incline angle values and the *slope index* and between the MCS values and the *intensity index*. For details regarding the computation of these two factors, we refer again to the above cited literature. We note however that, depending on the scale of study, the method can employ as seismic input either the peak ground acceleration (PGA) values derived from national scale hazard estimates, modulated on the basis of the site's amplification factors, or the intensity values that refer to the area's most representative earthquake (taking into account the worst seismic "scenario"). No matter the type of seismic input that is used, the *Intensity Index* will, implicitly or explicitly, account for the geo-lithological characteristics of rocks and soils, as these features will affect their response to seismic action in terms of amplification phenomena.

Thus, the shear wave velocities of each lithological unit will influence the computation of both the Factors A and C of the procedure (connected to lithology and seismic intensity, respectively). A thorough assessment of their values represents therefore a key issue for a correct zonation of the territory susceptibility on seismic-induced landslides.

The attribution of Vs values to the lithological units is a costly target, if field and/or laboratory measurements are involved. In the following, we show how a careful evaluation of the unit's geomechanical and geophysical features based only on literature studies may lead to results that we consider reliable for land planning targets. The procedure was applied at different scales in two areas of southern Italy: the Campania region and the Island of Ischia (Fig. 6) (Rapolla et al., 2010, 2012).

In Fig. 7a and b we show the lithological maps of the Campania region (1st level – large-scale study) and of the Island

Table 4. Litho-seismic unit classification for the territories of Campania region and Ischia Island. Amplification factors from Eurocode 8 (2003). Modified after Rapolla et al. (2010, 2012).

Campania region litho-seismic units (prevailing lithology and/or lithological assemblage)	Average Vs ($\mathrm{m\,s^{-1}}$)	Ground type/amplification factor
Thin- to thick-bedded sands and clays	250	Type C/1.25
Mainly thin-bedded clays, clastic limestones and locally slates; massive clays	300	Type C/1.25
Mainly thin-bedded arenites, clays and locally marls; massive sands; pyroclastic deposits, ignimbrites and tuffs	350	Type C/1.25
Alternating gravels, sands and clays; thin- to thick-bedded conglomerates, arenites and clays; mainly thin-bedded clastic limestones, marls and clays; pyroclastic deposits with minor lavas	400	Type B/1.25
Thin- to thick-bedded clastic limestones with minor marls and clays	450	Type B/1.25
Massive gravels	500	Type B/1.25
Bedded marls with limestone	550	Type B/1.25
Massive or thick-bedded arenites, thick-bedded clastic limestones and marls	600	Type B/1.25
Thick-bedded clastic limestones with minor clays	750	Type A/1.00
Lavas; travertines; massive conglomerates	800	Type A/1.00
Limestones and dolomites; evaporites	1000	Type A/1.00
Island of Ischia litho-seismic units	Average Vs ($\mathrm{m\,s^{-1}}$)	Ground type/amplification factor
Sands and filling materials	150	Type D/1.35
Reworked pyroclastic deposits	180	Type C/1.25
Pyroclastic deposits	200	Type C/1.25
Debris deposits	250	Type C/1.25
Tuff (un-welded facies)	300	Type C/1.25
Tuff (welded facies, disrupted at the surface)	360	Type B/1.25
Pumice breccias and welded scoriae	400	Type B/1.25
Siltstones	600	Type B/1.25
Lavas	700–800	Type A/1.00

of Ischia (2nd level – intermediate-scale study). In the Campania region (Fig. 7a), landslides occur mainly in the areas characterized by flysch lithologies, represented by the 2nd, the 3rd and the 4th litho-seismic units in Table 4. Their low values of shear wave velocity are due to a high content of clay, to the presence of pervasive discontinuities and to the consequent high water content, mainly in the rainy periods. Moreover, these units are characterized by significant lithological heterogeneities, often involving very small volumes of material, and consequently by a low degree of cohesion. This leads to slope instability (deep-seated slides often evolving in soil flows) both in static and dynamic conditions.

On Ischia (Fig. 7b) the main lithological units involved in the seismic-induced instability phenomena of the island are (a) a welded tuff formation in correspondence with the main relief of the island and (b) debris deposits covering the tuff in the Piedmont areas. The mentioned tuff formation is classified as "soft rock" and is affected by exfoliation, weathering and thermo-chemical alteration processes. The debris deposits and soils on the Piedmont areas derive from the

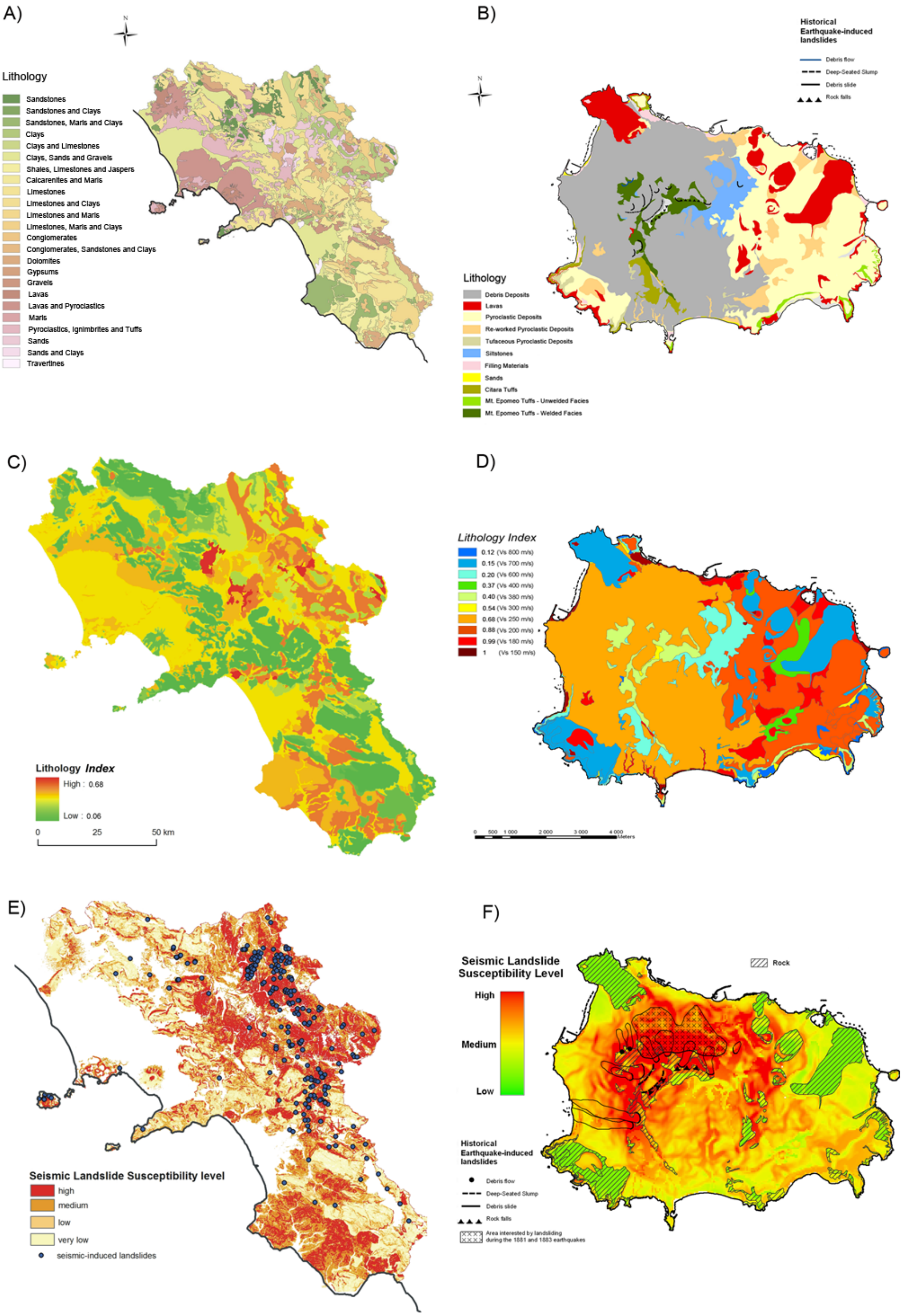

Fig. 7. Maps of the lithological units (**A** and **B**), *lithology indexes* (**C** and **D**) and *susceptibility indexes* (**E** and **F**) of two areas of southern Italy. Modified after Di Nocera and Matano (2011) and Rapolla et al. (2010, 2012).

degradation of the tuff, and their granulometric characterization shows mainly sands with a negligible clay fraction.

The variable amount of clay (high content in some areas of the Campania region and negligible amount on Ischia) and the different extension of the study areas make the two analyses a good test for the validation of the procedure in different conditions.

The Vs values of each lithological unit of the study areas were identified on the basis of the data reported in literature, e.g. Nunziata et al. (2004) and Di Giulio et al. (2008) for the Campania Region, and Guadagno and Mele (1995) for the Ischia Island. This allowed the lithological units shown in Fig. 7a and b to be unified in 11 different litho-seismic units for Campania and 9 litho-seismic units for Ischia, on the basis of their average Vs values and ground types/amplification factors (Table 4).

In Fig. 7c and d we show the maps of the *lithology indexes* obtained for the two study areas by the application of the zoning procedure. Regarding the Campania region, we can observe several areas with medium and high values of the *Lithology Index* (Rapolla et al., 2012) (Fig. 7c) located in correspondence with the widespread flysch lithologies. On Ischia the highest *lithology indexes* are mainly located on the northwestern side of the island, which is characterized by loose and in some cases re-worked pyroclastics deposited on gentle slopes (Rapolla et al., 2010) (Fig. 7d).

In Fig. 7e and f, we show the maps of the *susceptibility indexes* obtained for the two study areas. In both cases, the distribution of the highest susceptibilities resulted in consistency with the distribution of the documented historical seismic-induced landslide data. We note that the obtained maps have a semi-quantitative meaning as they provide a degree of susceptibility in relative terms. As the Vs characteristics of most of rocks and soils depend on the variation of the rainfall amount, both the *lithology* and *susceptibility indexes* may be seasonally dependent, assuming different values, if referring to rainy or dry periods within the year. While for Ischia, the limited area of the island (approximately a hundred km^2) and the negligible clay fraction in the deposits should not significantly change the overall picture of the *lithology* and *susceptibility index* maps of the island, for the Campania region these two indexes may undergo significant seasonal variations. This is due to the size of the region (ca. 10 000 km^2), its morphological characteristics (which influences precipitation amount and distribution) and the presence of clay in the deposits of different areas of the region. All these factors will make the susceptibility vary in differentiated ways in different areas, depending on the clay content, the season and the morphology. In order to try to overcome this uncertainty, to each litho-seismic unit it was assigned the lowest possible shear wave velocity value within its variation range. This allowed the authors to refer to the worst possible "scenario" for the studied areas (for scenario-based earthquake hazard studies, see, e.g. Babayev et al., 2010). In the case of Ischia, this was done by considering high saturation conditions, typical of rainy seasons, for the island's weathered tuff and re-worked pyroclastic deposits. As mentioned, this may lead to a reduction in the Vs values of about 5 %. Regarding the Campania region, the worst possible "scenario" was accounted for by carefully evaluating the clay content of the litho-seismic units in Table 4 and estimating the relative Vs reduction with respect to similar lithologies with negligible clay contents, and, again, considering high saturation conditions typical of rainy seasons.

5 Concluding remarks

Shear wave velocity values have a fundamental role in connection with the mitigation of seismic hazard, as their low values are an indicator for site amplification phenomena, and thus they may highlight areas susceptible to seismically induced landslides. The Vs values and the modulus of lithological units are strongly influenced by factors such as the degree of fracturing and faulting, the clay content and the saturation of the medium, which in turn is influenced by rainfall.

The results of different studies from literature on rock samples reported in this paper confirm the well-known reducing effect of water and clay (which includes a fair amount of water) on slope shear resistance. From a quantitative point of view, the studies converge in showing that, for a constant porosity and water saturation, an increasing amount of clay from 0 % to about 30 % may cause a reduction of about 12 % in the Vs and of about 50 % in the shear modulus values, whereas for a constant porosity and clay content, an increasing saturation degree from 0 % to 100 % may lead to a reduction of about 5 % in the Vs values. We note that this little variation (5 %) is influenced by the mainly homogeneous nature of the rock samples analyzed in the described literature studies. In presence of joints, fault planes and slipping surfaces, much lower rock mechanical characteristics (shear resistance, cohesion) may be expected. We add that rock shear wave variations depend also on the scale of observations: the reduction in clay shear resistance connected to the presence of smear joints and/or to fault planes is in fact only reflected when observed at a detailed scale.

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References

Babayev, G., Ismail-Zadeh, A., and Le Mouël, J.-L.: Scenario-based earthquake hazard and risk assessment for Baku (Azerbaijan), Nat. Hazards Earth Syst. Sci., 10, 2697–2712, doi:10.5194/nhess-10-2697-2010, 2010.

Blangy, J. P., Strandenes, S., Moos, D., and Nur, A.: Ultrasonic velocities in sands-revisited, Geophysics, 58, 344–356, 1993.

Boadu, F. K.: Fractured rock mass characterization parameters and seismic properties: Analytical studies, J. Appl. Geophys., 36, 1–19, 1997.

Boadu, F. K. and Long, T. L.: Effects of fractures on seismic-wave velocity and attenuation, Geophys. J. Int., 127, 86–110, 1996.

Carcione, J. M., Gurevich, B., and Cavallini, F.: A generalized Biot-Gassmann model for the acoustic properties of shaley sandstones, Geophys. Prospect., 48, 539–557, 2000.

Castagna, J. P., Batzle, M. L., and Eastwood, R. L.: Relationships between compressional-wave and shear-wave velocities in clastic silicate rocks, Geophysics, 50, 571–581, 1985.

Di Fiore, V.: Seismic site amplification induced by topographic irregularity: Results of a numerical analysis on 2D synthetic models, Eng. Geol., 114, 109–115, 2010.

Di Giulio, G., Improta, L., Calderoni, G., and Rovelli, A.: A study of the seismic response of the city of Benevento (Southern Italy) through a combined analysis of seismological and geological data, Eng. Geol., 97, 146–170, 2008.

Di Nocera, S. and Matano, F.: Proposta di criteri per la definizione di geotematismi finalizzati a studi di carattere applicativo e territoriale mediante elaborazione di dati geologici della cartografia e della banca dati CARG. Note Brevi e Riassunti del Workshop ISPRA: "Il Progetto CARG e le attività di coordinamento del Comitato d'Area dell'Appennino meridionale: gli sviluppi delle conoscenze geologiche come strumento tecnico, applicativo e aministrativo", 15 dicembre 2010, Roma, Rendiconti Online della Società Geologica Italiana, suppl. 12, 45–48, 2011 (in Italian).

Eurocode 8: Design of structures for earthquake resistance, Part 1: General rules, seismic actions and rules for buildings, DRAFT No 6, Brussels, January 2003, European Committee for Standardization (C.E.N.), 208 pp., 2003.

Gaviglio, P.: Longitudinal waves propagation in a limestone: the relationship between velocity and density, Rock Mech. Rock Eng., 22, 299–306, 1989.

Goldberg, I. and Gurevich, B.: A semi-empirical velocity-porosity-clay model for petrophysical interpretation of P- and S-velocities, Geophys. Prospect., 46, 271–285, 1998.

Guadagno, F. M. and Mele, R.: I movimenti franosi indotti da terremoti nell'isola d'Ischia, in: Cinquant'anni di ricerca e di didattica del Prof. Felice Ippolito, edited by: Vallario, A., Bonardi, G., De Vivo, B., and Gasparini, P., Liguori, Naples, 127–137, 1995 (in Italian).

Han, D. H., Nur, A., and Morgan, D.: Effect of porosity and clay content on wave velocities in sandstones, Geophysics, 51, 2093–2107, 1986.

İnce, G. Ç.: The relationship between the performance of soil conditions and damage following an earthquake: a case study in Istanbul, Turkey, Nat. Hazards Earth Syst. Sci., 11, 1745–1758, doi:10.5194/nhess-11-1745-2011, 2011.

ISSMGE-TC4: Manual for zonation on seismic geotechnical hazards, The Japanese Society of Soil Mechanics and Foundation Engineering, 210 pp., 1999.

Jibson, R. W., Harp, E. L., and Michael, J. A.: A method for producing digital probabilistic seismic landslide hazard maps, Eng. Geol., 58, 271–289, 2000.

Kahraman, S.: The effects of fracture roughness on P-wave velocity, Eng. Geol., 63, 347–350, 2002.

Klimentos, T.: The effects of porosity-permeability-clay content on the velocity of compressional waves, Geophysics, 56, 1930–1939, 1991.

Klimentos, T. and McCann, C.: Relationships among compressional wave attenuation, porosity, clay content, and permeability in sandstones, Geophysics, 55, 998–1014, 1990.

Kowallis, B. J., Jones, L. E. A., and Wang, H. F: Velocity – Porosity – Clay content systematics of poorly consolidated sandstones, J. Geophys. Res., 89, 10355–10364, 1984.

Leucci, G. and De Giorgi, L.: Studio degli effetti delle fratture sulla variazione di velocità delle onde P ed S, 22nd National Conference GNGTS, Rome, 18–20 November 2003, 2003 (in Italian).

Louie, J. N.: Faster, Better: Shear-Wave Velocity to 100 Meters Depth from Refraction Microtremor Arrays, B. Seismol. Soc. Am., 91, 347–364, 2001.

Marion, D., Nur, A., Yin, H., and Han, D.: Compressional velocity and porosity in sand-clay mixtures, Geophysics, 57, 554–563, 1992.

Miles, S. B. and Keefer, D. K.: Comprehensive Areal Model of Earthquake-induced Landslides: Technical Specification and User Guide, USGS, Open-File Report 2007-1072, 69 pp., 2007.

Nath, S. K. and Thingbaijam, K. K. S.: Seismic hazard assessment – a holistic microzonation approach, Nat. Hazards Earth Syst. Sci., 9, 1445–1459, doi:10.5194/nhess-9-1445-2009, 2009.

Nunziata, C., Natale, M., and Panza, G.F.: Seismic characterization of Neapolitan soils, Pure and Appl. Geophys., 161, 1285–1300, 2004.

Nur, A., Mavko, G., Dvorkin, J., and Galmudi, D.: Critical porosity: a key to relating physical properties to porosity in rocks, Leading Edge, 17, 357–362, 1998.

OPCM – Ordinanza del Presidente del Consiglio dei Ministri del 20 Marzo 2003: Primi elementi in materia di criteri generali per la classificazione sismica del territorio nazionale e di normative tecniche per le costruzioni in zona sismica, Supplemento Ordinario alla "Gazzetta Ufficiale" n. 105 dell'8 Maggio 2003 – Serie Generale, Ministero della Giustizia, Rome, 285 pp., 2003 (in Italian).

Paolucci, R.: Amplication of earthquake ground motion by steep topographic irregularities, Earthq. Eng. Struct. Dynam., 31, 1831–1853, 2002.

Pham, N. H., Carcione, J. M., Helle, H. B., and Ursin, B.: Wave velocities and attenuation of shaley sandstones as a function of pore pressure and partial saturation, Geophys. Prospect., 50, 615–627, 2002.

Raymer, L. L., Hunt, E. R., and Gardner, J. S.: An improved sonic transit time-to-porosity transform, SPWLA 21 Ann. Logging Symp., 8–11 July 1980, 1–12, 1980.

Rapolla, A., Di Nocera, S., Matano, F., Paoletti, V., and Tarallo, D.: Regional zonation on seismic-induced landslide susceptibility: application of a new procedure to Campania, Southern Italy, Nat.

Hazards, 61, 115–126, 2012.

Rapolla, A., Paoletti, V., and Secomandi, M.: Seismically-induced landslide susceptibility evaluation: application of a new procedure to the island of Ischia, Campania Region, Southern Italy, Eng. Geol., 114, 10–25, 2010.

Riepl, J., Zahradnìk, J., Plicka, V. P., and Bard, Y.: About the Efficiency of Numerical 1-D and 2-D Modelling of Site Effects in Basin Structures, Pure Appl. Geophys., 157, 319–342, 2000.

Theilen-Willige, B.: Detection of local site conditions influencing earthquake shaking and secondary effects in Southwest-Haiti using remote sensing and GIS-methods, Nat. Hazards Earth Syst. Sci., 10, 1183–1196, doi:10.5194/nhess-10-1183-2010, 2010.

Thompson, E. M., Baise, L. G., Kayen, R. E., Tanaka, Y., and Tanaka, H.: A geostatistical approach to mapping site response spectral amplifications, Eng. Geol., 114, 330–342, 2010.

Tosaya, C. and Nur, A.: Effects of lack of parallelism in sample faces on measurements of ultrasonic attenuation, Geophys. Res. Lett., 9, 5–8, 1982.

Wald, D. J. and Allen, T. I.: Topographic Slope as a Proxy for Seismic Site Conditions and Amplification, B. Seismol. Soc. Am., 97, 1379–1395, 2007.

Wang, S. and Hao, H.: Effects of random variations of soil properties on site amplification of seismic ground motions, Soil Dynam. Earthq. Eng., 22, 551–564, 2002.

Watanabe, T. and Sassa, K.: Velocity and amplitude of P-waves transmitted through fractured zones composed of multiple thin low-velocity layers, Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 32, 313–324, 1995.

Wick, E., Baumann, V., and Jaboyedoff, M.: Brief communication "Report on the impact of the 27 February 2010 earthquake (Chile, $M_{\mathrm{W}} = 8.8$) on rockfalls in the Las Cuevas valley, Argentina", Nat. Hazards Earth Syst. Sci., 10, 1989–1993, doi:10.5194/nhess-10-1989-2010, 2010.

Wyllie, M. R. J., Gregory, A. R., and Gardner, G. H. F.: Elastic wave velocities in heterogeneous and porous media, Geophysics, 21, 41–70, 1956.