Shear wave velocity-penetration resistance correlation for Holocene and Pleistocene soils of an area in central Italy

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Keywords: cone penetration resistance, geophysical testing, regression models, shear modulus, shear wave velocity

ABSTRACT: With the aim of preventing and reducing the seismic risk in an area in Umbria, central Italy, of notable importance from a historic and economic point of view, the local government of the Umbria Region promoted a considerable seismic microzonation project. A widespread geotechnical investigation survey was carried out to this end, including sounding with undisturbed sampling, standard penetration tests, dynamic cone penetration tests, cone penetration tests, down-hole and cross-hole tests. The purposes of this paper are to summarise the results from field and laboratory testing performed to identify the main soil types detected in the area and to provide some empirical relations to estimate shear wave velocity from cone penetration resistance for the most representative geological formations of the region.

With the aim of obtaining relationships that are as reliable as possible, the available data were carefully selected. Moreover, it is well known that larger coefficients of determination are generally obtained when soil type, geologic age and sedimentary environment effects are considered in the regression equations, the selected data were subdivided and attributed to the two main geological units (Holocene and Pleistocene) present in the area. For each of these, grain size was classified using CPT data and two soil types (fine and coarse grained soils) were therefore identified. Regional correlations between shear wave velocity and penetration resistance parameters were thus assessed for all the four previously defined soil classes and for the two geological units without distinguishing fine-grained and coarse-grained soils.

The proposed relationships were compared with those suggested in the geotechnical literature by different authors and their predictive capacity was finally checked by comparing $V_S$ values estimated by means of the correlations and those measured in geophysical survey (cross-hole and down-hole tests). The results of these comparisons are also shown in this paper.

1 INTRODUCTION

The area under study is a part of the High Tiber Valley, on the border between Umbria and Tuscany, central Italy, and it is affected by a moderate but frequent seismic activity. In the region, tectonic, morphological and geotechnical conditions seem to be favourable to seismic ground motion amplification and local effects of soil instability. Thus, due to the artistic, historical, economic and industrial importance of the area, a relevant seismic microzonation project for the most important towns was promoted by the Umbria Regional Government. The study included the assessment of the local seismic effects by means of numerical analyses and seismological recordings and a widespread site investigation survey was carried out for complete (geometrical and geotechnical) characterisation of the subsoil.

In order to perform several numerical one- and two-dimensional ground response analyses, it was necessary to estimate the shear stiffness at small strain of the subsoil layers, particularly where data from geophysical tests were not available. As cone penetration tests (CPT) were the most common kind of survey carried out in the area, the use of the CPT data proved to be useful and the search for regional empirical relationships for estimating shear wave velocity, $V_S$, starting from CPT parameters (in order to calculate stiffness profiles necessary for the numerical analyses also at those sites not directly explored with seismic tests) represented one of the objectives of the seismic microzonation study.

This paper describes the preliminary analyses and the procedures adopted to reach this objective and the results obtained.
2 SITE DESCRIPTION AND GEOTECHNICAL PROPERTIES OF SOILS

The High Tiber Valley represents a Plio-Pleistocene basin where the tectonic de-stressing activity caused the formation of a complex system of faults and where lacustrine and fluviolacustrine sediments were deposited in the subsequent Villafranchian Age. The most recent tectonics are still active, as shown by the high frequency of seismicity. In the basin, Villafranchian sediments formed a succession with a thickness of about 400 m, consisting, in its lower part, of a mainly clayey-silty lacustrine units and, in its upper part, of a gravelly-sandy-silty, and in places clayey, units. In a more recent age, the valley was affected by complex erosion and fluvial sedimentation phenomena, which led to the formation of recent alluvial deposits and several orders of sedimentation phenomena, which led to the formation of a complex system of faults and alluvial terraces (Crespellani et al., 1997). Thus, the clayey-silty lacustrine units. In a more recent age, the valley was affected by complex erosion and fluvial sedimentation phenomena, which led to the formation of recent alluvial deposits and several orders of sediments at greater depths. Holocene alluvium and terraced alluvium, and materials of Pleistocene origin. The CPT profiles enabled classification of the materials encountered and estimation of their consistency or density. Relationship between $q_c$ and depth was also investigated, but since $q_c$ values are very scattered it does not seem possible to identify any trends with depth.

3 CONE PENETRATION TESTING

The cone penetration tests carried out as part of the project reached depths between 1.7 and 20.0 metres, through both materials of Holocene origin, recent and terraced alluvium, and materials of Pleistocene origin. The CPT profiles enabled classification of the materials encountered and estimation of their consistency or density. Relationship between $q_c$ and depth was also investigated, but since $q_c$ values are very scattered it does not seem possible to identify any trends with depth.

3.1 Soil type classification from the CPT data

Since one of the CPT’s peculiarities is the lack of soil samples, soil classification charts are usually employed to estimate soil type from CPT data. From the different classification charts available in the geotechnical literature, the one used in the simplified iterative approach proposed by Robertson & Wride (1997) was chosen by the Authors. This method suggested the use of a soil type index:

$$I_c = \sqrt{(\log F + 1.22)^2 + (\log Q - 3.47)^2}$$  \hspace{1cm} (1)

$Q$ and $F$ are the normalised cone penetration resistance and the normalised friction ratio defined as:

$$F = \frac{f_s}{q_c - \sigma_{vo}} \cdot 100$$

$$Q = \frac{q_c - \sigma_{vo}}{\sigma_{vo}}$$  \hspace{1cm} (2)

In the equation (2), $q_c$ and $f_s$ are tip cone resistance and friction ratio from CPT test, $\sigma_{vo}$ and $\sigma_{vo}$ are total and effective vertical overburden pressure, respectively.

### Table 1. Main physical and mechanical parameters from fine-grained soil samples of the two formations.

<table>
<thead>
<tr>
<th></th>
<th>$\gamma$ [kN/m$^3$]</th>
<th>$e_0$ [-]</th>
<th>$c'_{v}[kPa]$</th>
<th>$c'_{s}[kPa]$</th>
<th>$\phi'$ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hfg</td>
<td>19.72 0.63 0.21 0.04</td>
<td>17.33</td>
<td>25.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pfg</td>
<td>18.49 0.46 0.16 0.02</td>
<td>10.79</td>
<td>21.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20.90 0.81 0.31 0.09</td>
<td>25.51</td>
<td>28.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n.</td>
<td>17 17 15 15 9 9</td>
<td>28.18</td>
<td>28.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hgl</td>
<td>19.83 0.65 0.21 0.05</td>
<td>28.18</td>
<td>22.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pgl</td>
<td>18.00 0.33 0.09 0.02</td>
<td>11.77</td>
<td>9.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>21.94 0.98 0.35 0.10</td>
<td>57.88</td>
<td>28.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n.</td>
<td>29 28 14 14 11 11</td>
<td>22.00</td>
<td>28.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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If soil behaviour type index calculated by means of the equation (1) is $I_c < 2.6$, Robertson and Wride recommended normalising cone penetration resistance using the equation:

$$q_{c1N} = \frac{q_c}{p_a} \left( \frac{p_a}{\sigma_{vo}} \right)^{0.5} \quad (3)$$

and calculating the new value of $I_c$ using $q_{c1N}$ instead of $Q$. In equation (3) $p_a$ is the value of the reference atmospheric pressure, expressed in same units of $q_c$ and $\sigma_{vo}$. If the $I_c$ value thus calculated is greater than 2.6, a normalisation of cone penetration resistance similar to equation (3) but using an exponent 0.75 instead of 0.5 should be used to calculate a new value of $I_c$ for such data. The values of normalised cone penetration resistance and normalised friction ratio obtained by means of the procedure described above can be eventually used to plot data on the soil classification chart (Fig. 3). On the chart classes range from organic soils, peats (class 2) to gravelly sands to dense sands (class 7). A zone for normally consolidated soils is also indicated; overconsolidated or cemented soils tend to take place above this area, while more sensitive soils are placed under.

In Figure 3 the examined CPT data are plotted on the above mentioned chart. The figure indicates that alluvial and prevalently fine-grained soils (Fig. 3a) seem generally to have overconsolidation ratio (OCR) values higher than Pleistocene fine-grained material (Fig. 3b), according to the experimental results from oedometric tests performed on both soil types (Fig. 2e). This may probably be attributed to the fact that in the area under study the materials of

![Figure 1. Geological map of the area under study.](image-url)
Pleistocene origin lie at a greater depth than the Holocene alluvium and as a consequence have lower OCR values. It is also possible to observe that in agreement with the laboratory and in situ testing carried out on these materials (Crespellani et al., 2002), the alluvial deposits are more heterogeneous than Pleistocene soils. In fact, Figure 3 also shows that alluvial sediments analysed are placed in the classes ranging from coarse-grained materials to clay and organic soil/peat.

4 DOWN-HOLE AND CROSS-HOLE TESTING

Twenty-two down-hole and two cross-hole tests, with two holes, were included in the geotechnical investigation survey and the shear wave velocity, \( V_S \), and compression wave velocity, \( V_P \), were measured.

Down-hole tests were performed with two receiver geophones and two different methods (true interval and pseudo-interval) were used to interpret recordings.

As already known, the true interval method can be only applied when two (or more) receivers are used. In this case, since receivers are positioned at different depths in the borehole, simultaneous monitoring of body waves for the same blow is performed and used in evaluation of wave velocities. When the pseudo-interval technique is applied, recordings of a single receiver are used and wave velocities are determined by using information from different measurement points for different impulses.

In Figure 4, \( V_S \) profiles are provided in the upper 30m of depth, separately for Holocene alluvium and Pleistocene lacustrine sediments, also including the results obtained from DH and CH tests from previous geotechnical investigation surveys (Crespellani et al., 1997) performed on the same area. The comparison between Figure 4a and 4b evidences that \( V_S \) values in Holocene materials are in average lower than in Pleistocene sediments and increase more rapidly with depth.

4.1 Comparison between Go values from field and laboratory tests

Resonant column and cyclic torsional shear (RCTS) tests were performed on 12 undisturbed specimens (4 for Holocene and 8 for Pleistocene soils), isotropically reconsolidated to the best estimate of the in situ vertical effective stress.

\( V_S \) values from in situ tests were compared with those obtained from the small strain shear modulus, \( G_s \), measured in laboratory tests, by means of the equation:

\[
\frac{G_s}{V_S^2} = C \cdot \frac{\rho}{\sqrt{V_P^2 - V_S^2}}
\]

Figure 2. Main soil characteristics (g.w.l. ranges from about 3 to 6m in depth where alluvial materials outcrop; it was found at depths greater than 10m where lacustrine deposits take place on the ground surface).

Figure 3. CPT-based soil classification by means of Robertson and Wride (1997) procedure.
\[ V_S = \frac{G_0}{\rho} \]  

(4)

The ratio \( V_S \)-field to \( V_S \)-laboratory for Holocene soils was on average equal to 1.71 and ranged between 0.87 and 2.44; for Pleistocene sediments it was on average equal to 1.62 and ranged between 0.85 and 2.62. \( V_S \) values obtained from laboratory tests are also represented in Figures 4a and 4b.

5 CPT DATA - \( V_S \) RELATIONSHIPS AND COMPARISON WITH OTHERS EXISTING CORRELATIONS

With the aim of increasing reliability of the correlations analysed, the CPT data and the \( V_S \) values were carefully selected, in accordance with the following criteria:

1. Data relative to the first two metres of soil were excluded from the processing, as this often consists of filling or vegetal soil.

2. All the values of the normalised tip cone resistance, \( Q \), and of the normalised friction ratio, \( F \), were averaged over one meter in depth, after having excluded the maximum value and the minimum. With the values thus obtained, the soil was classified at intervals of one metre, using the procedure of Robertson and Wride. Subsequently, the CPT data whose classification obtained with Robertson and Wride approach did not agree with the stratigraphy of the adjacent borehole were excluded from processing.

3. Recordings from down-hole and cross-hole tests whose S wave arrival time was not clearly identifiable were excluded from the processing.

In an initial phase of the research the data were analysed separating alluvial Holocene sediments from materials of Pleistocene origin and coarse-grained materials (for which the CPT data fall in regions 5, 6 and 7 of Robertson’s chart) from fine-grained ones (for which the CPT data fall in regions 2, 3 and 4 of Robertson’s chart).

As the geotechnical properties were observed to be essentially unrelated to depth in the explored verticals, for both the formations, it was retained opportune, also in accordance with the proposal already put forward by several Authors (Jamiolkowski et al., 1985; Baldi et al., 1989; Rix & Stokoe, 1991), to adopt a simple relationship as follow:

\[ V_S = \alpha \cdot q_c^{\beta} \]  

(5)

where \( V_S \) is expressed in m/s and \( q_c \) in MPa.

The coefficients \( \alpha \) and \( \beta \) of the regression for the various materials and the respective coefficient of determination, \( r^2 \), are given in Table 2, where it is possible to observe that the regressions determined regardless of geological origin, only maintaining a distinction between fine-grained and coarse-grained materials, showed the best fit to the experimental data.

Table 2. Coefficient of the regressions and coefficient of determination for the proposed empirical relations.

<table>
<thead>
<tr>
<th>n.</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( r^2 ) (eq. 5)</th>
<th>A</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( r^2 ) (eq. 6)</th>
<th>a</th>
<th>b</th>
<th>( r^2 ) (eq. 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hfg</td>
<td>25</td>
<td>211</td>
<td>0.20</td>
<td>0.83</td>
<td>140</td>
<td>0.30</td>
<td>-0.13</td>
<td>0.92</td>
<td>145</td>
<td>0.18</td>
</tr>
<tr>
<td>Pfg</td>
<td>21</td>
<td>193</td>
<td>0.32</td>
<td>0.81</td>
<td>182</td>
<td>0.33</td>
<td>-0.02</td>
<td>0.81</td>
<td>97</td>
<td>0.28</td>
</tr>
<tr>
<td>Hfg-Pfg</td>
<td>46</td>
<td>211</td>
<td>0.23</td>
<td>0.87</td>
<td>155</td>
<td>0.29</td>
<td>-0.10</td>
<td>0.91</td>
<td>146</td>
<td>0.17</td>
</tr>
<tr>
<td>Hcg</td>
<td>18</td>
<td>241</td>
<td>0.24</td>
<td>0.72</td>
<td>268</td>
<td>0.21</td>
<td>0.02</td>
<td>0.73</td>
<td>124</td>
<td>0.25</td>
</tr>
<tr>
<td>Pcg</td>
<td>12</td>
<td>230</td>
<td>0.25</td>
<td>0.63</td>
<td>172</td>
<td>0.35</td>
<td>-0.05</td>
<td>0.66</td>
<td>83</td>
<td>0.36</td>
</tr>
<tr>
<td>Hcg-Pcg</td>
<td>30</td>
<td>230</td>
<td>0.25</td>
<td>0.81</td>
<td>224</td>
<td>0.26</td>
<td>-0.01</td>
<td>0.81</td>
<td>113</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Comparison with analogous regressions available in the literature, is shown in Figure 5, after having obtained the values of \( G_0 \) from the equation (4). It can be observed that the path of the \( G_0 (q_c) \) functions on the bilogarithmic diagram found for mainly fine-grained materials (line 1a in the figure) and coarse-grained (line 1b in the figure), is almost parallel to that of the relationships proposed by Simonini and Cola (2000) and by Imai and Tonouchi (1982), in the modified version by Bouckovalas et al. (1989). Whereas the regressions obtained by Bouckovalas et al. (1989) and by Mayne and Rix (1993, 1995), for soft clays on the Greek coast and for different types of clay on different sites in the world, respectively, have a greater slope.

Subsequently an empirical relationship between \( V_S \) and both the resistance parameters obtained from
CPT, $q_c$ and $f_s$, was analysed. In particular, in accordance with what was proposed by Hegazy and Mayne (1995), an expression of the following kind was adopted:

$$\beta \alpha \beta \cdot \cdot \cdot = (6)$$

where $V_S$ is expressed in m/s, $q_c$ and $f_s$ in MPa.

The values of the parameters $A$, $\alpha$ and $\beta$ obtained for use in (6) are given in Table 2.

It may be observed that the values of $r^2$ for (6) are at least equal to those for (5), and are significantly greater for cohesive materials. The negative value of exponent $\beta$ (Table 2), with exception for alluvial coarse-grained materials, is due to the inverse trends of $V_S$ and $f_s$.

Despite the small number of data examined, this pattern seems reasonable observing that with an increase in the fine content, an increase in $f_s$ and a reduction in $V_S$ are to be expected. However, there is no experimental confirmation in literature relate to this, and even the $\beta$ values calculated by Hegazy and Mayne (1995) have opposite signs.

Finally the applicability of correlations that use correct and/or normalised values of $V_S$ and $q_c$ was analysed (Baldi et al., 1989; Andrus et al., 2001), using the following relation:

$$V_{S1} = a \cdot (q_{c1N} \cdot f_s)^b$$

where:

$$V_{S1} = V_S \left(\frac{p_o}{\sigma'_v}\right)^{0.25} \quad q_{c1N} = \left(q_c / p_o\right) \left(p_o / \sigma'_v\right)^{0.5}$$

and $p_o$ is the value of the reference atmospheric pressure, expressed in same units of $q_c$ and $\sigma'_v$.

The regression coefficients $a$ and $b$, for the different materials, are given in Table 2, where it is possible to observe that only in the case of coarse-grained Pleistocene materials the coefficient of determination is greater compared to that of the relationship (6). Comparison with regressions of a similar shape proposed by Andrus et al. (2001) is shown in Figure 6.

It is possible to observe that the exponent of $q_{c1N}$ depends on the age of the deposit. Coarse-grained soils, often consisting of gravels, are stiffer than sandy soil analysed by Andrus (Fig. 6b). In accordance with results already known in literature, cohesionless Pleistocene materials appear stiffer than cohesionless alluvial materials for most of the $q_{c1N}$ values analysed (Fig. 6b). Whereas as far as concerns the fine-grained sediments, even though the empirical regressions are closer to those discovered by Andrus, the older materials do not present greater stiffness (Fig. 6a).

5.1 Comparison between estimated and measured $V_S$ values

Figure 7 summarizes the comparison between the values of $V_S$ estimated by means of the three proposed empirical relations from the penetration resistance parameters, averaged over one meter in depth, and the experimental values from several geophysical testing performed in holes close to the CPT surveys.

The best agreement between predicted and measured values is obtained for fine-grained soils (full symbol in figure) and particularly by using equation (6) (figure 7b), in which both penetration resistance parameters, $q_c$ and $f_s$ are considered. Average and standard deviation of the ratio between $V_S$ measured ($V_{Sm}$) and estimated ($V_{S,e}$) by means of the equations (5), (6) and (7), for both fine-grained and coarse-grained soil, are summarised in Table 3.
Table 3. Average and standard deviation of the ratio between VS measured (VS,m) and estimated (VS,e) by means of the proposed empirical relations.

<table>
<thead>
<tr>
<th></th>
<th>Fine-grained soils</th>
<th>Coarse-grained soils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{V_{S,e}}{V_{S,m}}$</td>
<td>$\frac{V_{S,e}}{V_{S,m}}$</td>
</tr>
<tr>
<td>eq. (5)</td>
<td>0.976</td>
<td>0.100</td>
</tr>
<tr>
<td>eq. (6)</td>
<td>0.986</td>
<td>0.086</td>
</tr>
<tr>
<td>eq. (7)</td>
<td>0.966</td>
<td>0.141</td>
</tr>
</tbody>
</table>

The predictive capabilities of the suggested relationships can be also observed in figure 8 where the VS profile obtained from a cross-hole test was compared with those estimated by means of the relations (5), (6) and (7) from the data of a CPT survey carried out near to the holes of the CH test.

The results obtained show substantially good agreement at the examined vertical between measured and estimated VS values. However, remarkable discrepancies can be noted in thin layers of materials that present sudden increases in $q_c$ values.

6 CONCLUSIONS

This paper has presented the results of a study performed on an area in central Italy for the assessment of regional empirical relationships between shear wave velocity, $V_S$, and penetration parameters resistance, $q_c$, and $f_s$. Data were collected from 22 cone penetration tests, 22 down-hole and 2 cross hole tests, with reference to two of the main formations present in the examined area: terraced and recent Holocene alluvium and lacustrine and fluviolacustrine Pleistocene sediments.

After a careful selection of the data, soils were
classified according to Robertson and Wride approach (1997), distinguishing fine-grained from coarse-grained soils for each of the two formations.

Data included in the 4 identified classes of soil were analysed and correlations $V_S = f(q_c)$, $V_S = f(q_c, f_s)$ and $V_{SI} = f(q_c, N_l)$ were proposed, with $V_{SI}$ and $q_{c1N}$ being the normalised values for $V_S$ and $q_c$ respectively.

From the results of this study the following conclusions may be made:

1. the CPT data showed that penetration resistance parameters, $q_c$ and $f_s$, were substantially unrelated to the depth in the examined area;
2. all the suggested relationships present high coefficients of determination; the correlations that only consider the distinction between Holocene and Pleistocene formation, regardless of the grain size composition, show on average the best fit to the experimental data;
3. the adequacy of the proposed correlations was tested by means of comparison between a $V_S$ measured profile from CH and the predicted values from a CPT close to the CH soundings. Relevant discrepancies were founded only in a thin layer of coarse-grained soil with a sudden increase in $q_c$;
4. among the three proposed correlations (5), (6), (7), the one which considers both the resistance parameters obtained from CPT, $q_c$ and $f_s$, namely (6) shows the best fitting to the experimental data, except for Pleistocene coarse-grained soils;
5. as cone penetration test has become increasingly popular in recent years and widely used in the region, the proposed correlations can be useful in preliminary estimate of the stiffness at small strain of deposits which can be attributed to the two most widespread geological formations encountered in the area under study.

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