In situ dynamic characterization of soils by means of measurement uncertainties and random variability

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Abstract

In situ dynamic characterization of natural granular soils by means of V_S values is accomplished by direct and indirect investigation techniques. Integration among those types of field test are encouraged by Eurocode 8 through correlations amongst V_S and N_{SPT} but this does not suggest the best correlation formulation among the ones presented over the last thirty years. Besides such correlations can provide highly disperse values of V_S. Thus a rational design of investigation campaign and measurement interpretation and calculations appears to play an important role in dynamic characterization of granular soils accomplished by in situ tests. It should rely on selecting the best fitting correlation formulations site by site according to soil types, their random structures and the characteristics of investigation techniques measured dynamic soil properties. An application of statistical approach to the issues previously sketched is carried out in the Pomigliano d'Arco urban area where Down-Hole and Standard Penetration tests were performed for dynamically characterizing the foundation soils. Assessment of uncertainties in V_S values should allow the performance of hazard analyses and reliability-based design in seismic areas.
Keywords: Down-Hole tests, SPT, model uncertainty, N_{SPT}-V_S relations, measurement errors.

1 Introduction

Dynamic characterization of granular soils at low strain level is the first step of seismic response analyses or of soil basement dynamic classification whenever is needed for building designing activity in urbanized areas. Various "in field"

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techniques have been developed and enhanced to that scope as Down-Hole and Standard Penetration Test or similar tests. The first device allows to directly record arrival times and convert them into V_S and V_P; whereas the second one gives indirectly the velocity V_S by means of correlations, developed by different authors over the years, with the number of blow counts N_{SPT}. Such direct and indirect techniques for V_S estimation are concerned with uncertainties and suffer the inherent variability and heterogeneity that granular soil deposits show.

Accordingly it should be useful to recognize the most affecting sources of uncertainties for the two types of investigation techniques in order to make them more reliable whenever geostatistical approach is employed.

The study presented below deals with the proposal of statistical methods to improve the reliability of V_S values both from direct and indirect measure. As indirect device concerns, that are N_{SPT} measurements, the uncertainties in N_{SPT} values and uncertainties given by the transformation models will be taken into account.

2 V_S direct measurements and their interpretation

A common geotechnical in field test to measure shear wave velocity (V_S) is the Down-Hole test. It is a punctual investigation and it exploits the theory of refraction of waves in order to measure the first arrival times of S and V waves.

Figure 1: Down-Hole tests setting at Pomigliano d'Arco town.

Besides geophysics investigates the real soil deposits with a lot of approximations and simplifications because they are very complex and heterogeneous media in spite the theory of refraction and propagation of elastic waves within a homogeneous and elastic medium.

Hence, the interpreting phase of recorded arrival times play a fundamental role even though it is heavily influenced by the operator judgement. This is the most relevant issue why the application of reliability approach to that dataset is a hard work. Let us now consider the case of five Down-Hole tests performed in the urban area of Pomigliano d'Arco, a town near Naples (Italy), where a microzonation activity was recently carried on (fig. 1). Five borings of 30m depth were investigated and five Down-Hole tests were performed. Direct analyses of soil samplings over the five profiles show successions of pyroclastic sandy deposits from 0 to 16m depth and lava and sand alternate levels from 16m to 30m. This evidence can be caught from the five time vs. depth diagrams illustrated in fig. 2.

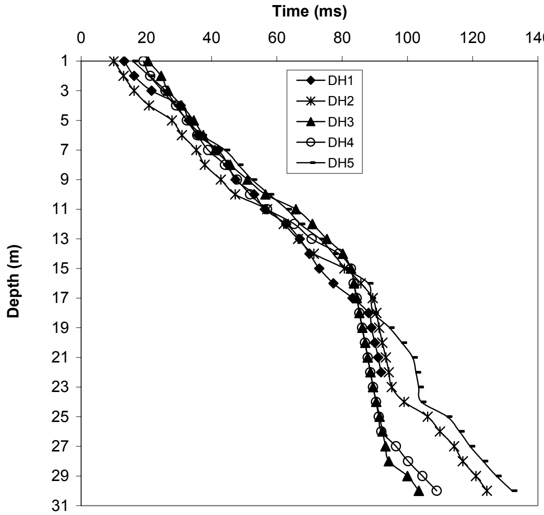

Figure 2: Time versus depth diagram for the five Down-Hole tests performed in Pomigliano d'Arco town.

As can be pointed out at 16m a change in arrival times is evident but more variability can be drawn deeper. Furthermore some differences in resulting V_S values can be read, affecting seismic strata distribution, whether different methods are employed. Table 1 shows V_S values according to the following two interpretation procedures of time vs. depth diagrams:

(1) it considers interval velocities and defines a seismic stratum where rapid variations occur;

(2) it searches for a linear trend on time vs. depth diagram then sketches bounds where the trend visibly changes.

Table 1: V_S values (m/s) calculated by means of method (1) and method (2) from the five Down-Hole tests.

	DH1		DH2		DH3		DH4		DH5	
Depth (m)	1	2	1	2	1	2	1	2	1	2
1	240	227	211	278	278	250	281	264	196	212
4										
5				258						
10										
11				185		208				
12								146		191
14										
15						1121		1167		
16										
17					1126		1020		1204	1176
18			1040	1064						
19	1053	1034							441	282
21										
22										1212
23									1209	
24			258	236						
25								281	233	251
28										
29					230	286	227			
30										

Table 1 shows different seismic strata and different V_S values. Even when seismic strata for the two methods correspond, there are no way to rationally lead to unique V_S values.

This subjectivity cannot be solved and its final dispersion in V_S values cannot be treated or reduced in any way.

In order to address this issue Cherubini and Vessia [5] suggested using statistical techniques on time vs. depth diagram to derive a trend and residuals that recognize vertical variability structure of the deposit. That approach would be useful whenever Down-Hole tests are performed in the nearby and eventually supported by seismic refraction tests in order to get also horizontal variability structure. On the contrary, as can be seen in fig. 1, in Pomigliano d'Arco those five seismic tests are set far each other. For that reason only their vertical variability structures shall be considered. Thus another procedure is presented here with the scope of defining V_S values from time vs. depth diagrams in a unique and repeatable fashion. The technique applied was proposed by Vivatrat

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[6] and it was born and developed for continuous vertical measurements performed in bore holes as cone penetration test (CPT). Here it is successfully applied to Down-Hole tests.

2.1 Vivatrat procedure applied to V_S estimation

The Vivatrat filtering procedure allows to statistically treat measures by selecting those data which result to be odd values and affect the mean trend and the variability of the data set. The Vivatrat procedure can be sketched in the following items: (1) To plot the unfiltered measures (arrival time) versus depth. (2) To divide the complete dataset of measures in layers of extension D: it is suggested to vary from 0.5m to 2.5m. In this case, the space lag between measures is 1m, thus it is assumed D=1m not to reduce the resolution of measures for "outlying peak" detection. (3) Calculation of mean μ_i and standard deviation s_i for each sub-layer identified. (4) Calculation of the "representative dispersion" S_r which is the minimum value among the following expressions:

$$S_r = \frac{1}{2}\left(S_{i+1} + S_i\right) \quad (1)$$

$$S_r = \frac{1}{2}\left(S_{i-1} + S_i\right) \quad (2)$$

$$S_r = \frac{1}{2}\left(S_{i+1} + S_{i-1}\right) \quad (3)$$

where Si-1, Si and Si+1 are the standard deviations calculated for sub-layers i-1, i and i+1 respectively. (5) To filter the measures which lie beyond the following limit values:

$$\mu_i \pm A \cdot S_r \quad (4)$$

where μ_i is the mean value within the sub-layer i, S_r is the characteristic standard deviation and A is the coefficient of the limiting band which can assume a value belonging to the interval (0.5; 2.5). In this case, four value of A were attempted: 0.5m, 1m, 1.5m and 2m. Thus for final results just A=1m is accounted for due to the fact that 0.5m eliminates quite all of the data, 1.5m filters as much data as 1m; finally 2m allows quite all of the data set to be accounted for.

Accordingly table 2 summarizes results for the five Down-Hole shear wave velocities filtered by means of the Vivatrat procedure.

Comparing table 1 and table 2 differences into seismic strata and V_S values can be found but they are not so relevant. Nevertheless from a methodological point of view, the Vivatrat procedure shows a real advantage because of its objectivity and repeatability. Moreover such method reduces the number of seismic strata making them more strictly correspond with lythological interfaces.

Table 2: Shear wave velocity values (m/s) and seismic strata subdivision from Vivatrat procedure for five Down-Hole tests.

<table>
<tr><th>Depth (m)</th><th>DH1</th><th>DH2</th><th>DH3</th><th>DH4</th><th>DH5</th></tr>
<tr><td>1
14</td><td rowspan="2">231</td><td rowspan="2">202</td><td>219</td><td>229</td><td rowspan="3">225</td></tr>
<tr><td>15
17</td><td rowspan="4">1135</td><td rowspan="3">1176</td></tr>
<tr><td>18
21</td><td rowspan="3">1037</td><td>1025</td></tr>
<tr><td>22
24</td><td rowspan="2">266</td><td>1136</td></tr>
<tr><td>25
30</td><td>236</td><td>217</td></tr>
</table>

3 V_S estimation by means of standard penetration tests

International building codes for seismic areas as Eurocode 8 [1] and the Italian "Testo Unico" [2] indicate the possibility of performing a dynamic soil characterization by means of the measurements performed over 30m depth of three parameters as shear wave velocity (V_S), blow count from standard penetrometer tests (N_{SPT}) and undrained shear strength (s_u). Besides, for granular soils only V_S and N_{SPT} are useful and from now on we will deal only with them.

Then parameter values should be converted into shear modulus at low strain rate, G_0 in order to carry out dynamic geotechnical analyses. At this stage V_S values are needed. That is the main reason why numerous correlation expressions between V_S and N_{SPT} are raised provided that standard penetrometer tests are widely performed and V_S is the most used parameter for in situ G_0 estimation.

Those empirical expressions are derived by means of different N_{SPT} and V_S database from all over the world but none provides high correlation coefficients. One well known expression is that by Ohta and Goto [4], whose database refers to alluvial plains in Japan:

$$V_S = 69 \cdot N_{SPT}^{0.17} \cdot z^{0.2} EF \tag{5}$$

where z= depth (m); E= the geological epoch factor: 1.0 (Holocene), 1.3 (Pleistocene); F= soil type factor: 1.0 clay, 1.09 fine sand, 1.07 medium sand, 1.14 coarse sand, 1.15 gravely sand, 1.45 gravel.

They provided their best relation between N_{SPT} and V_S (eqn. (5)) with a correlation coefficient R^2 equal to 0.86 with a probable error of 19.7%. Moreover it is worth noticing that Ohta and Goto also proposed to take into account different variables as effective stress, depth, soil type, geological epoch or only the N_{SPT} value formulating other empirical expressions reported within [7]. Accordingly they found that the equation where V_S depends only on N_{SPT}

variable has a correlation coefficient slightly different from those considering geological epoch, soil type and depth as the eqn. (5) (R^2=0.719, 27.4% for probable error). Over the years numerous were the researchers tried to manage the possible correlation between N_{SPT} and V_S but each formulation has not a wide applicability and problems on correspondence of V_S measured and estimated values are still opened. In this study the eqn. (5) has chosen, amongst the others, and applied to N_{SPT} measures performed at Pomigliano d'Arco in five boreholes where Down-Hole tests were carried out (see table 3). Table 3 reports N_{SPT} values over 16m depth because of the presence of lava and sands alternate levels under 16m for which standard penetration test results are often unreliable.

Table 3: N_{SPT} values measured over five soundings where Down-Hole tests were performed.

Depth (m)	N_{SPT}				
	S1	S2	S3	S4	S5
1					
2			20		
2.5	5				
4					15
5			25		
6	53				
7.5					49
8			16	10	
9	29	49			
10.5					26
11			24		
12	17	27			
12.9					27
14.5				63	
15		1			
16					

Shear wave velocity estimates from the application of eqn. (5) to the pyroclastic medium sands over the first 16m depth are illustrated in table 4 and compared with V_S measures from Down-Hole tests filtered by Vivatrat procedure. As can be seen differences in values are registered even though they don't show systematic trend. In fact sometimes V_S measured values are higher than the estimated one but other times the contrary is true. Moreover often the two types of values are near each other but not always and this occurrence apparently cannot be related to the depth or to the estimation errors.

Thus V_S indirect estimation would become a very uncertain activity which could lead to an unreliable geotechnical design if variability and uncertainties concerning to N_{SPT} measures and transformation models are not investigated.

Table 4: V_S values estimated by N_{SPT} and Vivatrat procedure applied to V_S (m/s) measurements performed by Down-Hole tests.

Depth (m)	V_S1	DH1	V_S2	DH2	V_S3	DH3	V_S4	DH4	V_S5	DH5
1										
2					183	219				
2.5	152	231								
4									201	225
5					229	219				
6	270	231								
7.5									278	225
8					233	219	215	229		
9	264	231	289	202						
10.5									267	225
11					266	219				
12	255	231	276	202						
12.9									280	225
14.5							331	229		
15			165	202						

4 Uncertainties concerning with SPT measurements

Standard penetration test (SPT) is a common tool for geotechnical characterization of building sites due to its economy and simplicity. Nevertheless most of the sources of uncertainties concerned with the N_{SPT} measures have not sufficiently quantified. A detailed list of 27 sources of uncertainties are illustrated by Zekkos *et al.* [3] but only three out of them can be taken into account by means of reliability analyses:

1. Soil inherent variability
2. Equipment uncertainties due to hammer efficiency, borehole diameter and sampler
3. Procedure uncertainties

Phoon and Kulhawy [7] summarized measurement errors and random variability commonly found for in situ tests. As regard N_{SPT} values three coefficient of variation (COV (%)) ranges are outlined for the three sources of uncertainties itemized above:

1. Random variability for clay and sand: 12%÷50%;
2. Equipment uncertainty: 5%÷75%;
3. Procedure uncertainty: 5%÷75%.

In the case studied the N_{SPT} values are not enough for carrying out a variability soil characterization. Accordingly in order to assess the reliability of V_S estimation by means of N_{SPT} measures and eqn. (5) by Ohta and Goto, the minimum values of the COV ranges reported are taken for the study. Moreover the variance related to the transformation model is calculated by the formulation of probable error (E) indicated by [4]:

$$SD_m^2 = \sum_{i=1}^{n} \frac{(V_c - V_o)^2}{n} = \frac{\ln(E+1)}{0.675} = 0.071 \quad (6)$$

where SD^2_m is the variance that represents the "model error"; V_c is the shear wave velocity calculated by eqn. (5); V_0 is the corresponding shear wave velocity in situ measured; n is the number of measures and E is the calculated probable error that is 19.7% for eqn. (5).

In order to measure the reliability of V_S estimated values by means of N_{SPT} measures and eqn. (5) variability and uncertainties are combined consistently using the second-moment probabilistic approach, reported by [7].

According to such approach the mean value and the variance characterizing an estimated variable ξ_d is given by the following expressions:

$$m_{\xi_d} \approx T(t, 0) \quad (7)$$

$$SD^2_{\xi_d} \approx \left(\frac{\partial T}{\partial w}\right)^2 SD^2_w + \left(\frac{\partial T}{\partial e}\right)^2 SD^2_e + \left(\frac{\partial T}{\partial \varepsilon}\right)^2 SD^2_\varepsilon \quad (8)$$

where T(·) is the "transformation model" or the correlation equation eqn. (5) for the case studied; t is the deterministic trend function or the mean value; SD2w, SD2e and SD2ε introduce variances concerned to inherent soil variability, measurement error and transformation uncertainty respectively.

Results from the application of the second-moment probabilistic technique are presented in table 5. The total coefficient of variation measures the reliability of estimate at each depth. Hence, for those values of COV higher than 50% the estimate results to be unreliable whereas those values of COV lower than 50% should be considered as reliable as the NSPT values result to be.

Table 5: Total coefficient of variation related to V_S estimated values by means of Ohta and Goto expression in terms of N_{SPT} measures from five boreholes.

V_S1	COV	V_S2	COV	V_S3	COV	V_S4	COV	V_S5	COV
152	83%	289	16%	183	25%	215	59%	201	37%
270	14%	276	28%	229	25%	331	14%	278	16%
264	25%	165	>100%	233	40%			267	28%
255	41%			266	30%			280	28%

5 Conclusions

In the paper two reliability studies are carried out on shear wave velocity determination by means of in situ tests: Down-Hole and Standard Penetration Tests. The first one is related to depth vs. arrival time diagrams from Down-Hole measures: a filtering procedure is applied in order to suggest a standard method by means of seismic strata detection and V_S value calculation.

The second issue attains the evaluation of reliability in estimation of shear wave velocity from N_{SPT} measures by means of Ohta and Goto relationship. The analysis considers the contributions of measurement errors in SPT, inherent variability of soil and transformation model error from eqn. (5) to the final V_S values. The study shows that often the reliability of V_S estimation, for the case studied, can be considered acceptable and can justify the differences in values between measured and estimated V_S.

Results from such work can be reviewed as a contribution to a more objective method for dynamic characterization of soils aimed at dealing with both foundation designing and local seismic response analyses.

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