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Evaluating soil liquefaction potential using Nakamura methodology in an experimental site

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ABSTRACT: Microtremor measurements is a cost-effective and non-invasive technique based on ambient vibrations recordings at ground surface. These records are used to estimate the fundamental frequency of soils, f_0, and its amplification ratio, A_0, based on the spectral ratio between the horizontal (H) and vertical (V) components of the measurements, and has been known worldwide as the Nakamura Method.

In the scope of the H2020 EU funded, LIQUEFACT project, which addresses the mitigation of the risks associated with the liquefaction induced due to the seismic action, in situ geotechnical tests were performed, including microtremor measurements, in the Lisbon area in Portugal.

Each measurement had an approximate duration of 40 minutes at 26 different sites, using a SYSCOM velocity sensor (MS2003+) connected to an SYSCOM acquisition unit (MR2002), considering an acquisition frequency of 400 Hz. The H/V identified peak frequencies ranging from 0.92 to 11.01 Hz and peak amplitudes ranging from 2.58 to 4.73.

The soil liquefaction potential using the Nakamura method is evaluated by the determination of the vulnerability index, *Kg*, which is determined with the values of fundamental frequency of soils, f_0, and its amplification ratio, A_0. With the *Kg* values, is possible to estimate the ground strain, γ, at a location and therefore make a first assessment of the potential for large deformations.

1 INTRODUCTION

Earthquakes have been one of the major causes of large human and economic losses in the last decades, which are dependent, not only from the type of seismic action (intensity, epicentre distance, duration), as from the local characteristics like the type of construction and geological formations that may exist (Panzera et al. 2017). Recently, there has been an increasing importance in the development of knowledge of local ground conditions, concerning the local site effects, with special focus on the estimation and evaluation of these effects, in order to predict and mitigate their effects on society.

Several physical phenomena (resonance effects, non-linearity of the behavior of soils; wave reflections and diffractions) affect the local seismic site response. The seismic waves registered at the surface, due to these phenomena, may suffer amplification or attenuation (Panzera et al. 2017).

Due to its low cost, non-invasive nature and simplicity the Nakamura method (or HVSR) has been widely used. Nakamura (2008), stated that is possible to estimate the fundamental frequency, f_0, and the local amplification ratio, A_0, of soil deposits, at a specific location, using measurements of ambient vibrations at surface. These parameters are obtained through the spectral ratio between the horizontal and vertical components (H/V). The value of the fundamental frequency (f_0) is representative, except for complex conditions Ghofrani and Atkinson (2014), however, regarding the amplification factor, A_0, the value is not reliable. Nakamura (1997) defined the vulnerability index, Kg, as a parameter that allows the estimation of the ground strain, γ, thus allowing to make an assessment of the displacements that may occur at a specific location. However, few studies have been developed in the validation of this technique for the estimation of ground strain. Recently, Herrera et al. (2018) developed a study on the assessment of the Nakamura methodology for evaluating soil liquefaction potential, where, in this paper the authors calculated the vulnerability index using the fundamental frequency obtained using HVSR measurements. They compared the obtained results from conventional methods (SPT and CPT tests), and showed that 82 % of the tests matched with the values determined with conventional method, concluding that this method can be an alternative for liquefaction assessment.

This paper presents the results of the microtremor measurements carried out in the pilot site selected in Portugal for the tasks of LIQUEFACT project (www.liquefact.eu). Regarding the soil liquefaction potential, it is discussed the reliability of the Nakamura method to predict high liquefaction potential, comparing with results from classic methods based in *in situ* tests.

2 EXPERIMENTAL SITE

For the experimental campaign, several sites in Portugal were studied within the scope of the H2020 EU LIQUEFACT project. As the Lezíria Grande area, in the municipality of Vila Franca de Xira, Portugal, is the area that showed the higher liquefaction susceptibly (Saldanha et al., 2017) the microtremor measurements took place in along this area.

2.1 *The study area*

With the information available due to the construction of the A10 Highway, was possible to develop the geotechnical characterization for the area under study. This characterization was based on in situ tests, such as: SPT (S) tests, Cross-hole (CS) profiles, CPTu (Cpt) tests, of which 2 are SCPTu, whose location is presented in Figure 1.

Figure 1. Location of the several tests along A10 Highway (adapted from LIQUEFACT, 2017)

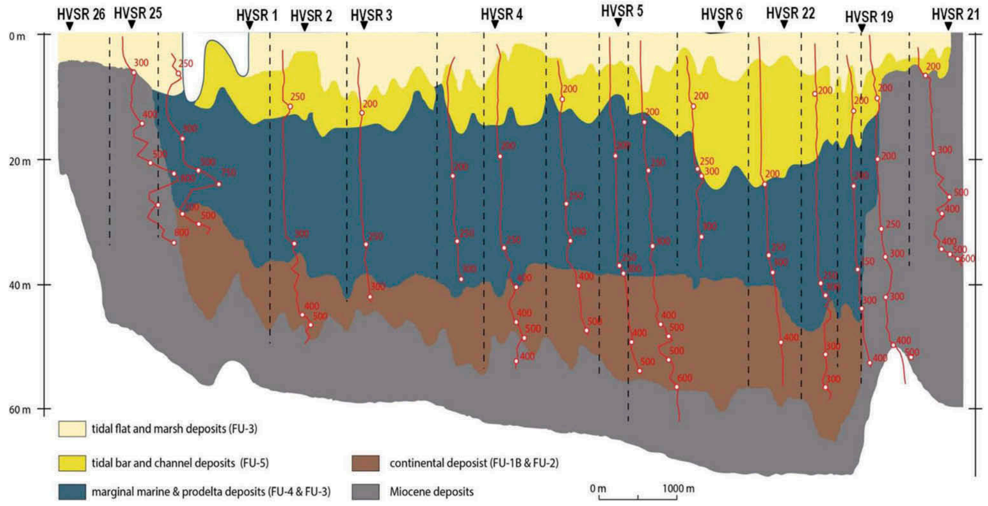

Figure 2. Geological profile of the A10 Highway (adapted from LIQUEFACT, 2017)

The geological map shows the existence of large Holocene deposits of sandy sediments in the south bank of the Tagus River, in the area under study. This basin is composed of tertiary sediments, reaching 2000m deep, with the deepest sediments with a layer of 200 to 400 m of thickness of continental sediments of the Palaeocene. In this layer of continental sediments, is possible to identify a layer of continental and marine sediments of the Miocene, reaching deeps around 800 m in some places. In Figure 2 is shown the geological profile in the zone of the A10 Highway, including Vs profiles from CH profiles (adapted from Vis et al., 2016).

From Figure 2, the A10 Highway geological profile can be defined as:

- Surface layer 5 to 6 meters thick and $200 \leq Vs \leq 300$ m/s (FU-3), formed by muddy clays, silty clay and clays, sometimes with intercalations of silts and fine sand, and coarser sands at surface;
- Sediment layer 15 m thick and $150 \leq Vs \leq 250$ m/s of fine, medium to coarse sands intercalated with silts and clays (FU-5);
- Marine fine grained sediments 20 and 30 meters thick and $200 \leq Vs \leq 250$ m/s (FU-4 & FU-3), formed by large volumes of clays and silty clays;
- Alluvial deposits 12 to 15 meters thick and $400 \leq Vs \leq 500$ m/s (FU-1B & FU-2) formed by coarse sand, sands and gravels, with a low percentage of fine grains;
- Lithified Miocene deposits 300 meters thick with $600 \leq Vs \leq 800$ m/s.

Based on the Vs profiles, it was determined the shear wave velocity of the upper 30 meters, Vs,30, and the NP EN 1998-1 (2010) ground type classification scheme was applied (Table 1).

Regarding $V_{s,30}$ values, the minimum value is 160 m/s (S25) and the maximum is 292 m/s (S203).

According to NP EN 1998-1 (2010), the ground type is near the limit between ground Type C (180 m/s < Vs,30 < 360 m/s - Deep deposits of dense or medium-dense sand, gravel or stiff clay) and Ground Type D (Vs,30 < 180 m/s - Deposits of loose-to-medium cohesion less soil, with or without some soft cohesive layers, or of predominantly soft-to-firm cohesive soil). 7 profiles are classified as ground type C and 8 profiles as type D.

Table 1. VS,30 and NP EN 1998-1 (2010) ground type for the A10 Highway.

Cross-Hole	203	S11	S6	S208	S16	S220	S22	S25	S225	S28	S32	S232	S37	S304	S42
Vs,30 (m/s)	292	167	203	167	168	181	181	160	185	172	165	164	159	167	216
Ground type	C	D	C	D	D	C	C	D	C	D	D	C	D	D	C

Figure 3. Location of ambient vibration measurements

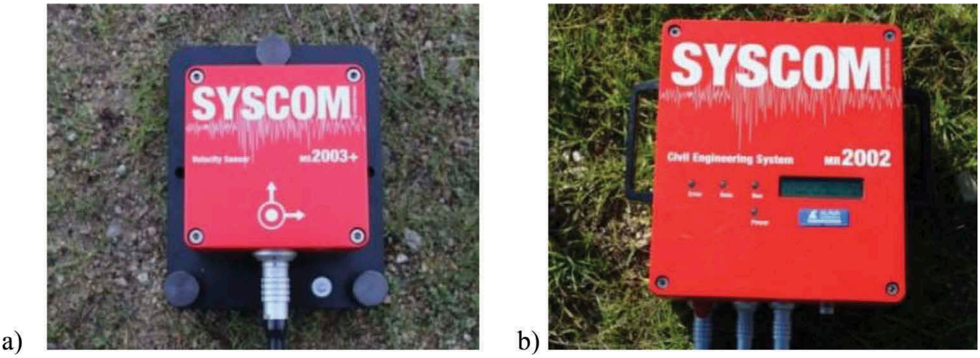

Figure 4. a) Three-dimensional velocity sensor (Model MS2003+); b) Acquisition unit (Model MR2002)

The site investigation comprised single station ambient vibration measurements (HVSR) at 11 sites along A10 profile (Figure 3).

The measurements were carried out using a three dimensional velocity sensor (Model MS2003+) (Figure 4a)), connected to an acquisition unit (Model MR2002) (Figure 4b)), which was connected to a laptop. The acquisition frequency for each recording is 400 Hz, with a duration of approximately 40 minutes.

3 HVSR RESULTS

Ambient noise recordings were analyzed with Geopsy software, which is an open source software, developed in SESAME Project (2004). In Table 2, the values obtained for HVSR

Table 2. Obtained values from the H/V curves for the A10 profile.

HVSR	26	25	1	2	3	4	5	6	22	19	21
f_0 (Hz)	1.98	1.14	1.14	0.90	1.61	1.18	1.14	1.18	1.22	1.06	11.01
A_0	4.65	3.71	3.88	4.02	2.58	3.51	3.70	4.16	4.73	4.05	3.32

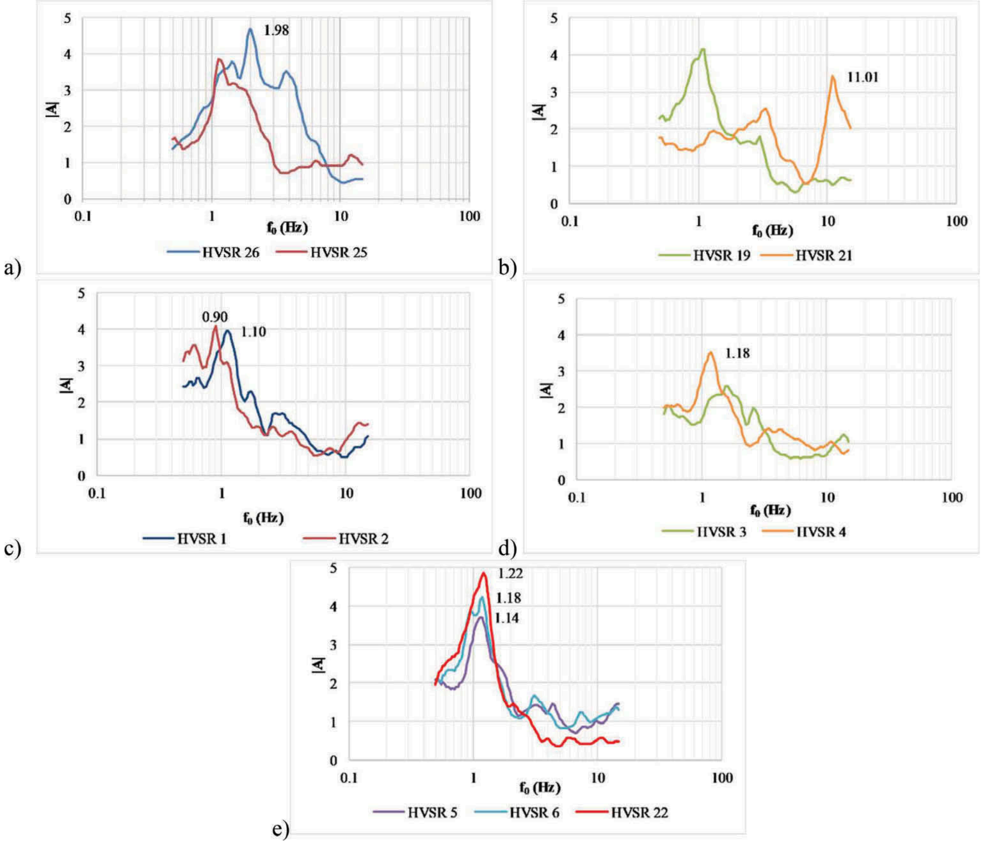

Figure 5. H/V curves for HVSR measurements in A10 Highway profile: a) and b) edge of the valley c), d) and e) - central zone

measurements in the A10 profile are presented. Figure 5a) and Figure 5b) plot the H/V curves obtained in the borders of the A10 Highway (HVSR 19, 21, 25 and 26). Figure 5c), d) and e) plot the H/V curves obtained in the central zone of the A10 Highway (HVSR 1 to 6 and HVSR 22).

Regarding the obtained values for the Amplification ratio, A_0, the obtained H/V curves show a single and clear peak (HVSR 1,4,5,6 and 22). The values of A_0, range from 2.58 to 4.73. Only for measurements HVSR 2,6,19,22 and 26 $A_0 > 4$.

The values of the fundamental frequency, f_0, reveal variability in the stratigraphy all along the profile, existing a clear evidence that this is a river valley zone:

- Edges of the valley with amplification peaks at high frequencies, namely f_0 = 1.98 Hz (HVSR 26) and f_0 = 11.01 Hz (HVSR 21), consistent with the geological profile (Figure 2).
- Central zone of the valley with amplification peaks at low frequencies, f_0 = 0.90 Hz (HVSR 2) until f_0 = 1.22 Hz (HVSR 22);

4 LIQUEFACTION POTENTIAL

The evaluation of the soil liquefaction potential using the Nakamura method is evaluated by the determination of the vulnerability index, K_g, which is determined with the values of fundamental frequency of soils, f_0, and its amplification ratio, A_0. With the Kg values, is possible to estimate the ground shear strain, γ, at a location, and therefore assess the likelihood of large deformations occurrence.

4.1 *Vulnerability index, K_g and estimated ground shear strain,γ*

Vulnerability index, K_g value is proposed as an index to estimate the ground shear strain, obtained from the fundamental frequency of soils, f_0, and its amplification ratio, A_0 of microtremor measurements. This index is a proxy of liquefaction potential, defined by Equation 1, and the estimated ground shear strain, γ, is given by Equation 2 (Nakamura, 1997, 2012).

$$K_g = \frac{A_0^2}{f_{0\,1}} \tag{1}$$

$$\gamma = \frac{K_g \times a_g}{\pi^2 \times V_{b1}} \tag{2}$$

Where, a_g, is the maximum ground acceleration and V_b is the shear wave velocity at the basement of the sediment layer, A_0, the amplification ratio and f_0, the fundamental frequency of soils, obtained from the H/V curves.

According to the given equations (1) and (2), and regarding the values of A_0 and f_0, presented in Table 2, and considering a_g = 0.28 g (m/s^2) and V_b = 200 (m/s), the vulnerability index, K_g, for the 11 sites, is given in Table 3.

Table 3 shows that the value of K_g increases proportionally with ground shear strain. From the analysis of the values of the estimated ground shear strain, γ, it can be seen that all sites, with the exception of HVSR 3 and HVSR 21, are vulnerable to high shear strains, larger than 1%. For these measurements, and considering the values of a_g, and V_b, the minimum value of K_g that induces a value of γ higher than 1%, is a value of K_g = 7.20.

4.2 *Soil liquefaction assessment*

According to Ishihara (1996), a value of shear strain if 1% can be used as first approximation of the threshold value for the large strain range, where significant structural change occurs in soil skeleton and pore water pressure generation, which may lead to liquefaction.

Table 3. Vulnerability ground index, K_g, for the 11 sites at the A10 Highway

Measurement	A_0	f_0 (Hz)	K_g	γ (%)
HVSR 1	3.879	1.140	13.20	1.84
HVSR 2	4.018	0.897	18.00	2.51
HVSR 3	2.585	1.608	4.15	0.58
HVSR 4	3.510	1.180	10.44	1.45
HVSR 5	3.700	1.140	12.01	1.67
HVSR 6	4.157	1.180	14.64	2.04
HVSR 19	4.048	1.065	15.39	2.14
HVSR 21	3.319	11.011	1.00	0.14
HVSR 22	4.728	1.222	18.30	2.55
HVSR 25	3.706	1.140	12.05	1.68
HVSR 26	4.649	1.976	10.94	1.52

Table 4. Vulnerability ground index, K_g, and Liquefaction potential assess from penetration tests

Measurement	A_0	f_0 (Hz)	K_g	γ (%)	Liquefaction potential (LIQUEFACT, 2017)
HVSR 1	3.879	1.140	13.20	1.84	High
HVSR 2	4.018	0.897	18.00	2.51	High
HVSR 3	2.585	1.608	4.15	0.58	High
HVSR 4	3.510	1.180	10.44	1.45	Medium
HVSR 5	3.700	1.140	12.01	1.67	High
HVSR 6	4.157	1.180	14.64	2.04	High
HVSR 19	4.048	1.065	15.39	2.14	High
HVSR 21	3.319	11.011	1.00	0.14	High
HVSR 22	4.728	1.222	18.30	2.55	High
HVSR 25	3.706	1.140	12.05	1.68	High
HVSR 26	4.649	1.976	10.94	1.52	High

In Table 3, only for measurements HVSR 3 and HVSR 21 the values of γ are lower than 1%, so it is expected that the soil, in these sites, have low liquefaction potential. In all the other measurement points, the values are higher that 1%, thus the liquefaction potential is high.

In the study area, several in situ tests were carried out in the construction of the A10 Highway, namely SPT (S) tests, Cross-hole (CS) profiles, CPTu (Cpt) tests, of which 2 are SCPTu, whose location is presented in Figure 1 With all the information from these tests, LIQUEFACT (2017) established the liquefaction potential for several areas. Table 4 presents the liquefaction potential within the scope of the Liquefact Project, for the 11 sites of the HVSR measurements.

In general, the values of γ>1% are compatible with the liquefaction potential from classic methods based in penetration tests. Thus, for this study the threshold value of K_g = 7.20 divides the site with high and low liquefaction potential.

5 CONCLUSIONS

The microtremor measurements are currently used to estimate the fundamental frequency, f_0, and corresponding local amplification factor, A_0, using the Nakamura method. These results were used to determine the vulnerability index, K_g, and consequently estimate the ground shear strain at a specific site. With these values, the soil liquefaction potential was evaluated, comparing the values of ground shear strain, with information obtained from other *in situ* tests.

Regarding the vulnerability index, K_g, and estimated ground shear strain, γ, the value of K_g increases proportionally with the ground shear strain. From the analysis of the values of the estimated ground shear strain, γ, is possible to conclude that all sites are vulnerable to high shear strains, larger than 1%, with the exception of HVSR 3 and HVSR 21. The minimum value of K_g that induces a value of γ higher than 1% is K_g = 7.20.

These values were compared with the liquefaction potential determined through classic methods based on penetration tests. In general, both approaches predict the same liquefaction potential level.

This paper shows that Nakamura method can be a fairly reliable methodology to assess liquefaction potential at very low cost.

More studies are needed to confirm the trends identified in this paper, considering different values of maximum ground acceleration, a_g, and shear wave velocity at the base of the sediment layer, V_b.

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