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Measured and computed dynamic characteristics of a hospital building in Bucharest

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ABSTRACT: The southern part of Romania is characterized by special soil conditions, i.e. thick soil deposits of Romanian Plain, leading to a long corner period of response spectra Tc=1.6s with associated large displacement demands in the Romanian Seismic Design Code P100-1 (2013). The stiffening approach to control the structural seismic response may therefore not be successful but the alternative solution of base isolation is promising. The first step towards this solution is to properly estimate the dynamic characteristics of buildings. The reinforced concrete frame structure of a hospital built in 2014 in the capital city Bucharest is investigated. It has an underground level and five stories and its shape is irregular. Its elastic dynamic characteristics under small amplitude vibrations are estimated using multi-sensor ambient vibration measurements combined with classical spectral analysis. The results are compared with numerical results obtained from the computation of a structural model which are the basis for the optimum base isolator design within the next step of the research project.

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1 INTRODUCTION

In earthquake prone regions, the functionality of hospitals after an important seismic event is required, in order to serve the possible injured people. Immediate occupancy requirements may be achieved by aiming an elastic seismic response, either by sufficient stiffening (whereas high response accelerations are expected that may produce damage to furniture and equipment) or by using base isolation (which preserves the building from damage by decoupling it from its foundation system), Arranz et al. (2017). A comparison between these two design approaches is planned to be performed for an existing hospital building built in Bucharest, the capital city of Romania, in a region for which the efficiency of base isolation is questionable (it is a high corner period region, T_c=1,6s, for which high displacement demands are expected, according to the Romanian Seismic Design Code P100-1/2013).

The above comparison will be analytically performed, based on structural models and nonlinear dynamic analysis. A good estimate of the dynamic characteristics of the building is needed for a realistic computer model. For estimating the building's modal frequencies in the case of elastic behaviour, ambient vibration measurements were performed on the hospital building, under normal occupancy conditions.

2 AMBIENT VIBRATION MEASUREMENTS

Ambient vibration measurements were performed with two purposes: (i) for the estimation of vibration characteristics for small amplitude motions, and (ii) for the calibration of the computer model. In case of such measurements, the building behaviour is considered as elastic, and the global stiffness of the building benefits from the cumulated contribution of all structural and non-structural elements.

The measurement equipment consisted of a portable 24 bits GEODAS acquisition system and one-directional 1-second velocity sensors (with frequency bandwidth 1÷20 Hz) produced by Buttan Service-Tokyo & Tokyo Soil Research Co., Ltd.

The ambient vibration measurements were performed in March 2019 simultaneously using 5 velocity sensors (all connected to one acquisition station). Unfortunately the complex hospital buildings block, the construction site and the neighbouring properties configurations did not allow the use of a reference point at ground level. The measurements could be performed only at the last (4th) floor and targeted the horizontal vibrations of the building. Measurements were done in the evening, with no works on the nearby construction site and with a limited medical activity in the building. Two sensors distribution layouts were considered, the sensors being first oriented on the longitudinal direction and after that on the transverse direction. Consequently, four measurement schemes were considered for analysis, Figure 1. For each measurement scheme, two samples of 10 minutes were recorded with a 100 Hz sampling frequency. The measurements duration is considered to be sufficiently long according to Brincker et al. (2003) who considered that in practice the time length of the recorded window should be at least equivalent to 1000 periods of the structure.

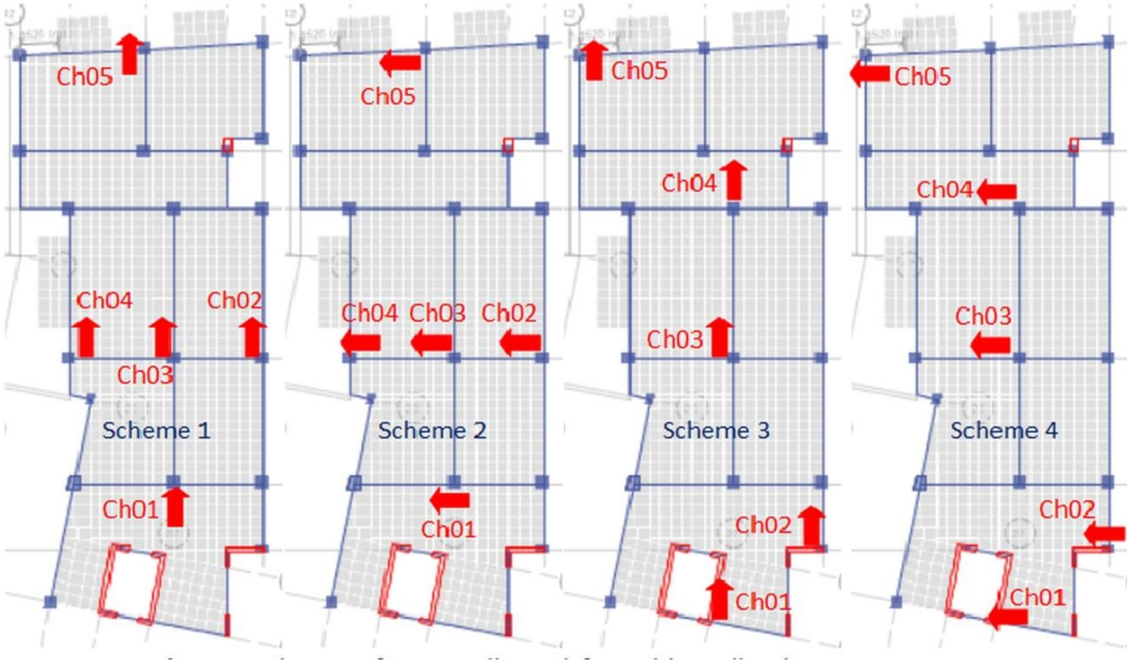

Figure 1. Schemes of sensors position for ambient vibration measurements.

Several techniques are available for the analysis of ambient vibration measurements, with various levels of complexity. For a preliminary analysis aiming the identification of modal frequencies, and since only structural output records are available, the most widely used and easiest approach was selected: the Peak Picking method (PP). In this frequency domain approach it is considered that peak spectral values appear at natural frequencies of building vibration. The peaks are usually identified on the Fourier Amplitude spectra, but cross spectra may also be considered. The method allows a reasonable estimation of modal frequencies (for example Iiba et al., 2004, Kohler et al., 2005, Ditommaso et al. 2010, Demetriu et al., 2012, Cha et al., 2014, Aldea et al., 2018, etc.). The coherences between sets of records from two measuring points, the autocorrelation functions, the phase angle and the Corner to Center Fourier Spectral Ratio (Ditommaso et al. 2010) were also studied for presenting the preliminary results. The offset removal was done using the whole record duration. A low-cut frequency of 0.1Hz and a high-cut frequency 25Hz were applied. A Parzen smoothing with 0.2Hz window was applied.

Ambient vibration time-histories are exemplified in Figure 2 for the longitudinal building direction. In Figure 3 are shown the Fourier amplitude spectra and the cross spectra for the records obtained in scheme 3, on building's longitudinal direction.

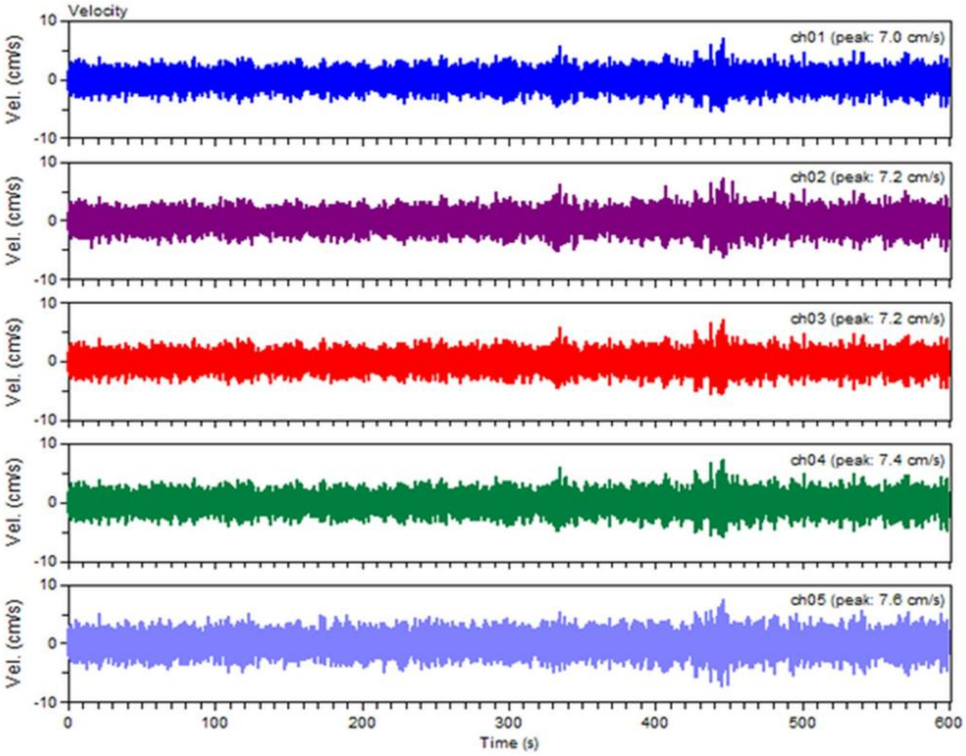

Figure 2. Ambient vibration time-histories - sensor scheme 3 (longitudinal direction).

In Figure 4 are shown the Fourier amplitude spectra and the cross spectra for the records obtained in scheme 4, on building's transverse direction.

A good stability of the major spectral peaks was observed for all records, on all spectra, for all directions.

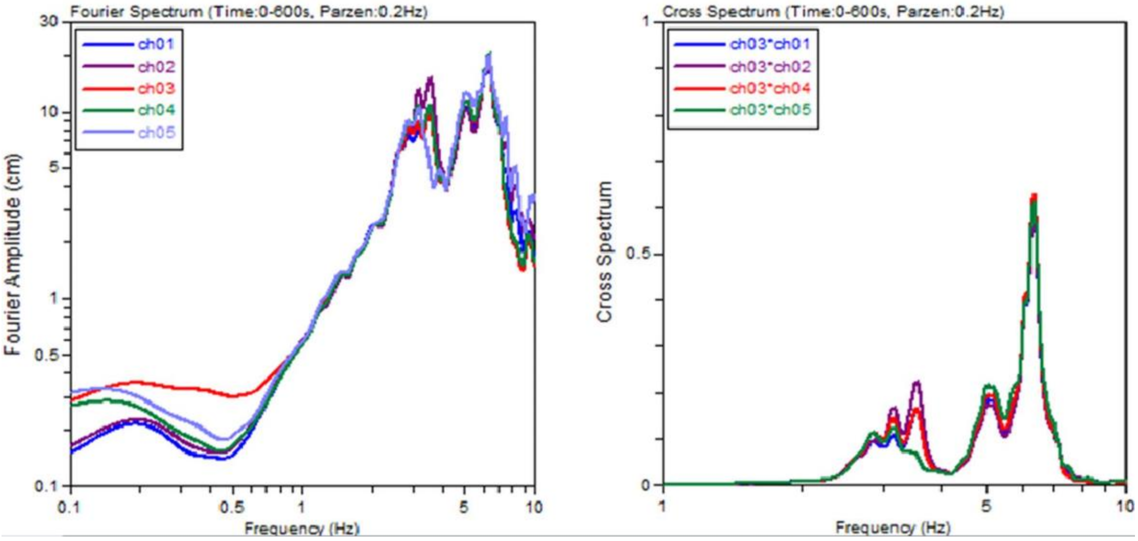

Figure 3. Fourier spectra and cross spectra - sensor scheme 3 (longitudinal direction)

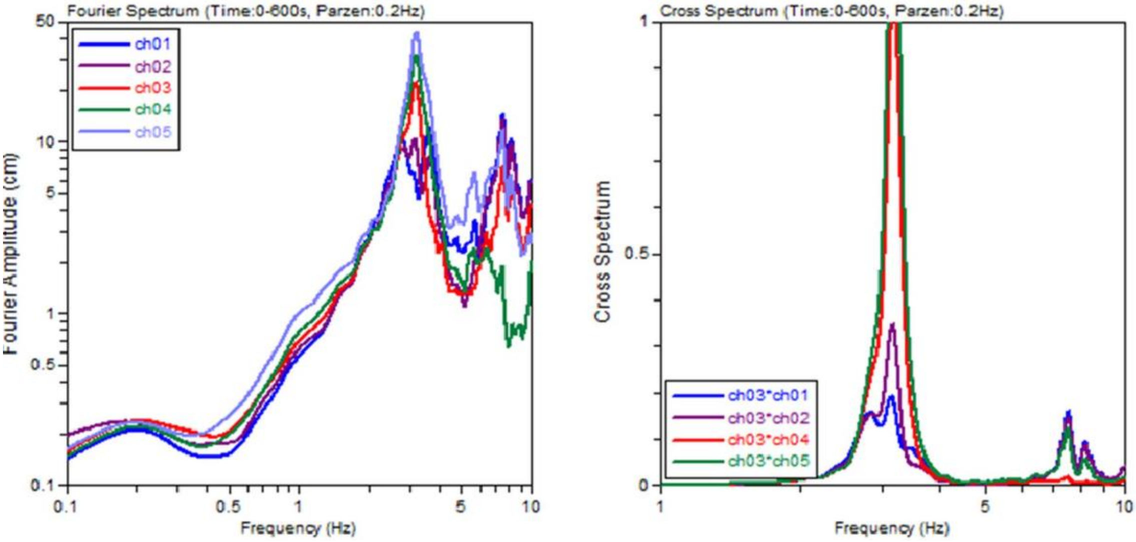

Figure 4. Fourier spectra and cross spectra - scheme 4 (transverse direction)

The results obtained from the analysis of ambient vibration measurements are given in Table 1 for longitudinal building direction and in Table 2 for the transverse one.

For each measurement scheme the results represent the averaged value of the results from PP method applied for the Fourier spectra, cross-spectra, and corner to centre spectral ratio, and for the two measurements.

The statistical indicators in the table are obtained using all the peak frequencies identified from all spectra, from both schemes (for longitudinal and respectively transverse directions) and the four measurements.

Table 1. Peak frequencies on longitudinal direction (Hz)

	f_1	f_2	f_3	f_4	f_5
scheme 1	3.55	5.04	6.29	8.24	13.50
scheme 3	3.56	5.07	6.32	8.31	13.58
average	3.56	5.06	6.31	8.30	13.54
standard deviation	0.04	0.07	0.03	0.08	0.09
coefficient of variation	1.00%	1.33%	0.43%	0.96%	0.65%

Table 2. Peak frequencies on transverse direction (Hz)

	f_1	f_2	f_3	f_4	f_5
scheme 2	3.16	7.52	8.30	10.14	13.46
scheme 4	3.16	7.53	8.19	10.19	13.48
average	3.16	7.53	8.24	10.16	13.47
standard deviation	0.03	0.03	0.06	0.07	0.11
coefficient of variation	0.94%	0.43%	0.76%	0.67%	0.80%

Supplementary, at the "central" point (location of Ch03 in Figure 1), two sets of ambient vibrations were recorded (20 minutes length, 100Hz sampling rate), using a Cityshark II acquisition system (Chatelain et al., 2012) and a Lennartz Le3D-5s velocity sensor. The data processing was performed with Geopsy software (http://www.geopsy.org/). In Figure 5 are presented the Fourier amplitude spectra for the transverse (N) and longitudinal (E) building directions, confirming the above results.

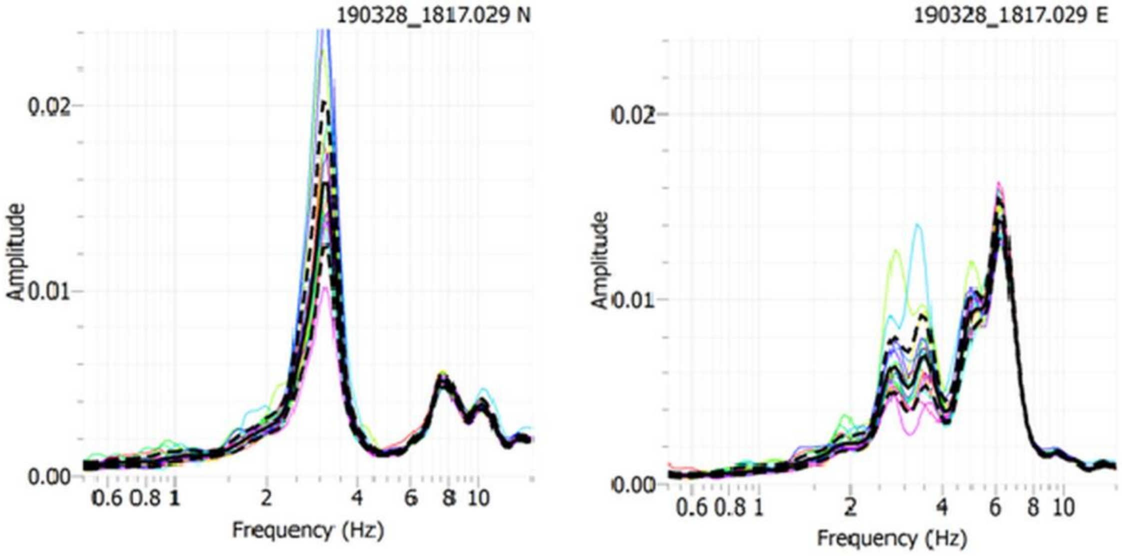

Figure 5. Fourier amplitude spectra for transverse (left) and longitudinal (right) building directions at the "central" point location.

3 MODEL DESCRIPTION AND MODAL ANALYSIS RESULTS

The hospital building was modelled with ETABS software, CSI (2013). The existing building is part of a building assembly having a common basement, but the model in this study considers only the underground level beneath the building. A fixed support structure at ground level was modelled too, but showed less consistent modal analysis results compared with the results from ambient vibration measurements. The layout of the structure is almost rectangular (cca. 12 x 28 m) and has a setback over the ground floor (see Figure 6). The overall building height is 20.1 m (3.55 m for underground level; 3.50 m for ground floor; 3.2 m for levels one to three and 3.45 m for level 4).

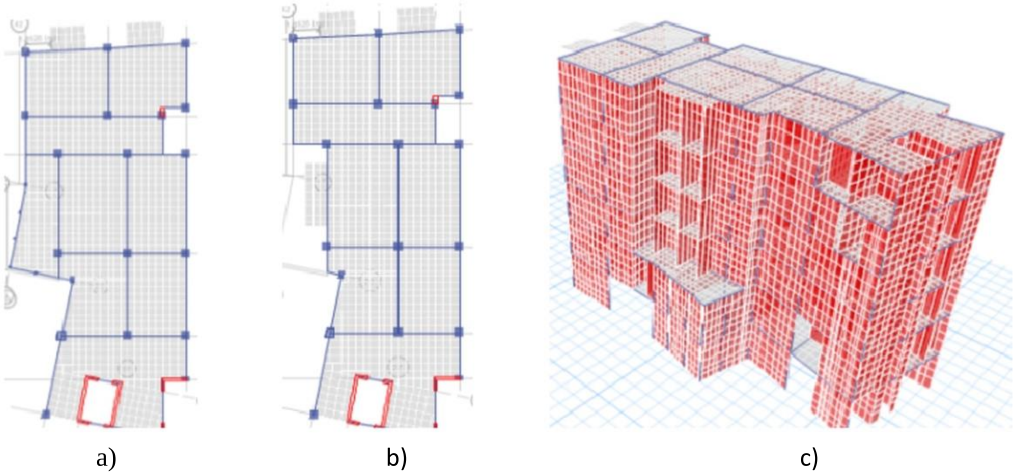
a) b) c)

Figure 6. Building layout: a) ground floor; b) upper stories; c) 3D model.

Modal analysis results (from finite element computer models) are often compared with results from ambient vibration measurements, and updated / calibrated models may match the experimental results, Ivanovic et al. (2000), Ventura et al. (2005), Demetriu et al. (2012), Fernandez Lorenzo et al. (2015), Riccio et al. (2017).

Since for comparison with ambient vibration results, the elastic building behaviour is required, unreduced stiffness was considered for the structural and non-structural building materials. Columns and beams were modelled as frame elements, walls and slabs were considered shell elements. The structural building material is reinforced concrete, C25/30.

Load assigns on floors were considered for finishing and terrace. Live and snow loads were also taken into account, according to the Romanian Design Codes CR0 - Basis of structural design and CR 1-1-3 Snow loads (2012).

For low amplitude vibrations (like ambient vibrations), structural as well as non-structural elements provide stiffness to the building. Therefore two types of non-structural elements were also included in the model: closure walls (made of 20cm thick masonry with autoclaved aerated concrete) with glass openings, and interior walls (made of plasterboard and having a thickness of 10cm or 15cm). Bricks with strength equal to 6 N/mm^2 and mortar M5 were considered for the masonry walls. Taking into account a 2.5cm / 1.5cm thick plaster layer (exterior/interior wall face), a combined modulus of elasticity of 7767 N/mm^2 was defined for the closure walls, according to CR6 (2013).

The openings of the closure walls are filled with glass (thickness 1.25 cm for the window panel and reduced self weight because only 4 mm are actually glass), having a reduced modulus of elasticity equal to 35000 N/mm^2, in order to take into account the connection to the wall and the opening frame, Lord (2003). When taking into account the real glass thickness of 4 mm, a disturbance of the eigen modes of the structure was observed, because only the thin glass walls vibrated. Modelling the glass openings influences the eigen period of the building by changing the second or third decimal value. Compared to the other non-structural elements it is a low influence, but taking into account too thin glass panels disturbs the entire model.

For the plasterboard interior walls a modulus of elasticity equal to 2500 N/mm^2 was taken into account, according to the producer's technical sheet.

Modal analysis was performed for the building model. Information regarding the first six building eigen modes is shown in Table 3. As expected, due to the fact that one plan dimension of the building is over two times larger than the other one and because structural and non-structural elements have a rather random position distribution, translation in longitudinal direction and torsion are coupled (23% displacement amplification at building corners, due to torsion). The deformed shape of the layout at the top of the structure is shown in Figure 7 for the first two eigen modes.

Table 3. Modal analysis results

Mode number	1	2	3	4	5	6
Frequency [Hz]	3.17	3.60	4.48	10.31	11.90	14.29
Participating mass [%]	70% → translation	20% ↑ translation 51% torsion	51% ↑ translation 19% torsion	13% → translation	2% ↑ translation 10% torsion	9% ↑ translation 3% torsion

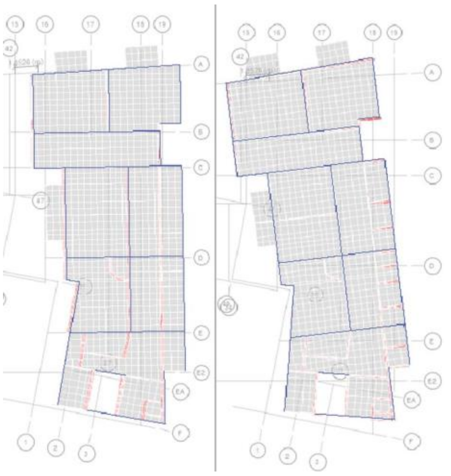

Figure 7. Mode shapes for the first two eigen modes.

4 FINAL CONSIDERATIONS

Ambient vibration measurements were performed at the last floor of a hospital building in Bucharest. The recorded data were analysed using the widely-used Peak Picking method (PP), for estimating the peak frequencies that characterise the building vibration in case of small amplitude motions. The preliminary results presented in Table 1 and Table 2 indicate the main peak frequencies. For such a peculiar building layout with an irregular distribution of structural elements, the identification of sway and torsional modes proved to be difficult, confirming the limits of the PP method.

The modal analysis of the computer model which includes the non-structural elements, Table 3, showed a good match for the first peak frequencies on both transverse direction (3.17 Hz versus 3.16 Hz, corresponding to a period of ~0.32s) and longitudinal direction (3.60 Hz versus 3.55 Hz, corresponding to a period of ~0.28s). The analytical results also indicate a complex dynamic behaviour, with significant coupling between translation and torsion.

The continuation of the study should include the use of more advanced approaches for the analysis of ambient vibration, a detailed study of the floor displacements at the measuring points, and a damping assessment. Nevertheless, based on the recorded ambient vibration measurements a final computer model may be fixed and considered as a basis for the analytical study of the two possible design solutions that are able to ensure the specific requirements of hospital functioning after a strong seismic event: sufficient stiffening or by base isolation.

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