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SYSTEM IDENTIFICATION OF CODE CONFORMING LOW-RISE RC BUILDING IN LALITPUR, NEPAL

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Abstract. *System identification of a code conforming low-rise reinforced concrete frame building in Kathmandu, Nepal is reported in this paper. The fundamental vibration period and damping ratio of the building were determined using ambient vibration records taken in three floors of the building. Ambient vibration measurements were taken using three triaxial accelerometers. Two methods of system identification, Welch spectral method and N4SID method, are used to estimate the modal properties. Fundamental vibration periods of the four-storied building estimated from non-parametric Welch spectral method are 0.292s and 0.289s in the two orthogonal directions. The corresponding results from the parametric state-space N4SID method are 0.266s and 0.264s in the orthogonal directions. The corresponding damping ratios are estimated to be 6.3% and 6.9%. These periods are longer than that of a simplified finite element model of the building assumed to be fixed at the supports. This indicates that the flexibility of the soil under the building foundation, plays an important role in the vibration frequencies of the structure.*

1 INTRODUCTION

Civil engineering structures are frequently exposed to dynamic loads in their service lives. Dynamic actions such as earthquake and strong winds can cause severe damage to such structure, or in case of milder actions, impart damages that are not visible immediately, but can accumulate over time. . Also, repeated actions on the structure leads to fatigue of structural elements. These phenomenon cause softening of the structure, which can mean degradation of stiffness and/or strength of its force resisting elements. As a result, the structure becomes more vulnerable to future environmental actions. Identification of such damages, especially those that are not visible on the surface, is important for timely remedial actions so that damage aggravation and accumulation over time can be avoided. Structural system identification and health monitoring is therefore a very important and growing research field in civil engineering.

System identification or an experimental modal analysis is a mathematical framework to identify dynamic properties of a structure from measured vibration and potentially excitation forces. System identification using vibration measurement at different times can reveal potential damage and its accumulation in the structure manifested in the form of change in its dynamic properties. This method has specific advantage over the other methods; they are non-destructive and able to identify damage that is not visible on the surface. Moreover, the structure can remain operational during testing, which can be a continuous process. Also, artificial excitation is often not needed , and ambient vibration induced by traffic or wind actions can be used There are two main genres of mathematical methods for system identification, parametric methods [3] and non-parametric methods [6]. In this study, both methods are used for system identification of a code conforming RC building located in Kathmandu, Nepal.

Finite element modeling based on mechanical properties and geometry of the structural systems can also be used to estimate their modal parameters. Reliability of the numerical results depends on assumption made to create model. There are several uncertainties involved in such modeling, for example in material properties, rigidity of connections, conditions of the soil supporting the foundation, etc., which introduce simplifying assumptions and engineering judgements in finite element modeling. These uncertainties translate to uncertainties in the estimated dynamic behavior of the structure. In addition, as the structure ages, its dynamic properties change. If the structure is subjected to strong loading or repeated moderate loading, it can lose part of its stiffness, which results in change of its dynamic behavior. System identification can be used to identify such changes and calibrate/update finite element models, which can then be used for analyzing its safety and/or designing retrofitting schemes. As dynamic characterization studies are limited in Nepal [9], this study considers a code conforming four-storied residential building located in Lalitpur metropolitan city, Nepal. Sawaki et al. [9] performed system identification of a four-storied residential building using aftershocks and ambient vibration records and concluded that the non-parametric method results in unrealistic damping ratios. To this end, this study incorporates both non-parametric and parametric methods to perform system identification.

2 CASE STUDY BUILDING

The studied residential building is situated in a densely populated area of Kathmandu Valley nearby the Bagmati River. The building is a four-story residential building constructed in 2013. The structural configuration of the building is a reinforced concrete frame with brick infill walls. The moment resisting frame structure consists of concrete columns, beams, and floor slabs. Locally made brick with cement-sand mortar is used as infill walls on the building. The infill walls contribute significantly to the overall stiffness of the building [8].

Figure 1 shows the structural layout of the building showing location of beams and columns. The building is asymmetrical in plan with off grid columns and beams. All the rectangular columns have section size of 300×230mm except the circular columns that have diameter of 230mm. All the beams have section size of 230×355mm including uniform slab thickness of 100mm. Concrete used in the building for casting of primary structural elements is ordinary concrete with mix proportion of 1:2:4 (cement: sand: aggregate) equivalent to M15 grade concrete. The specified characteristics compressive strength of a cube [150mm] in 28days for M15 concrete is 15MPa with modulus of elasticity 19365MPa (IS 456:2000 [2], modulus of elasticity, $E_c = 5000\sqrt{f_{ck}} \approx 19365$MPa). Structural reinforcement used in the building are deformed steel bars of Fe415 grade. The specified minimum 0.2% proof stress or yield strength of corresponding grade steel is 415MPa. The estimated strength of the infill walls is 2.5 MPa with modulus of elasticity 1750 MPa.

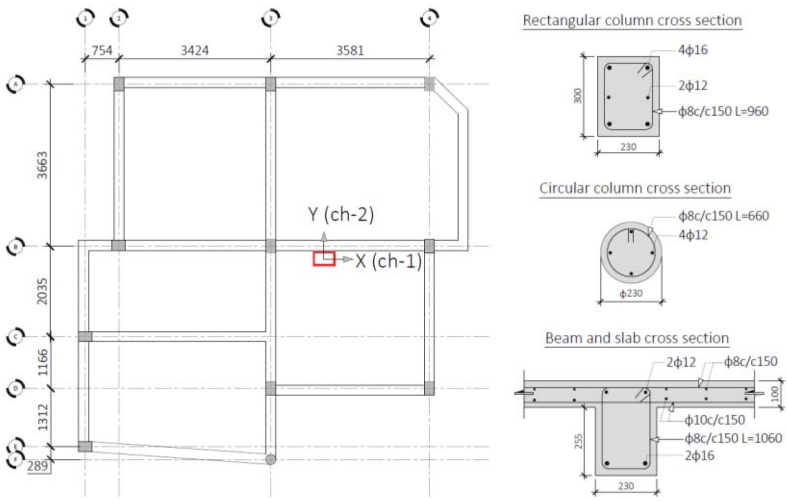

Figure 1: Structural layout of the building showing beams and columns and their cross sections. The red rectangle shows the location of accelerometer and orientation of the instrument sensor axis are indicaed with the arrows.

3 SYSTEM IDENTIFICATION

3.1 Ambient vibration measurement

Three digital accelerometers were installed on three different floors to record ambient vibration of the building. The instruments were located on the first second and third floor. Figure 1 shows the location of instruments (red rectangle) on plan view of the building. All three instruments on different floors were aligned vertically. The accelerometers used are ETNA2 units manufactured by Kinemetrics Inc. Direction of the measurement with respect to accelerometer sensors is indicated by co-ordinate axis shown in Figure 1.

3.2 Welch spectral method

This is a non-parametric method of system identification. This method estimates the frequency response function of the structure based on frequency-domain representations of its excitation and response. Using the Fourier transforms of measured input and output, an empirical estimate of the complex frequency response function, $\hat{H}(\Omega)$, can be obtained. Alternatively, estimates of power spectral densities of the excitation and response can be used as

$$\left|\hat{H}(\Omega)\right|^2 = \frac{\left|S_{yy}(\Omega)\right|}{\left|S_{uu}(\Omega)\right|} \tag{1}$$

where $S_{uu}(\Omega)$ and $S_{yy}(\Omega)$ are the power spectral densities (psd) of excitation and response, respectively, and Ω is the circular frequency.

Because of the inherent variability of Fourier Amplitude Spectra (see, for example, Rupakhety and Sigbjörnsson, 2012 [10]), some form of smoothing needs to be performed on periodogram estimates of psds. The Welch spectra reduces the variation in the psds by dividing the signals into different segments and averaging their spectral estimates. For a stationary signal, the Welch spectra provides an estimate of the true spectra of the random process. In case of ambient vibrations, the excitation can be assumed to be a white noise, and from Equation 1, an estimate of the system transfer function normalized by the variance of the excitation is obtained directly from $S_{yy}(\Omega)$. The natural frequencies can be obtained from the plot of squared amplitude of the complex frequency response function by picking the peaks. For system with small damping values, up to 10% of the critical damping, the peak of the plot occurs close to the natural frequency of the system. The frequencies and most of the power of the response gets concentrated in a narrow band of frequencies around the peak. If the damping ratio of the system is higher, the peak lies away from the natural frequency of the system and the power spectrum becomes wider. Response of a lightly damped structure excited with white noise process can be modelled as a narrow band process. The damping ratio of the structure can be estimated from the half power bandwidth method, which is based on the following equations [4]:

$$\xi = \frac{f_2 - f_1}{2f_n}$$
$$\Delta f = f_2 - f_1 = 2\xi f_n \tag{2}$$

Where, Δf is the half-power bandwidth defined in the frequency band where the power density of the response reduces to half its value at the peak; f_1 and f_2 are linear frequencies at corners of half power and f_n is the linear frequency of the peak which is approximately equal to the undamped natural frequency of lightly damped systems. This method is straightforward when power spectral density function contains one dominant peak, which is the case for damped single degree of freedom systems. For multiple degrees of freedom systems, multiple peaks corresponding to different vibration modes can often be observed. Identification of higher modes can sometimes be difficult due to noise in the measured signal. Identification of higher modes is more difficult when signal to noise ratio is large, which is often the case with ambient vibration measurements.

To apply this method to the case study building, recorded time series data from all the floors channel 1 (ch-1 Figure 1) and channel 2 (ch-2 in Figure 1) were divided into twenty equal segments. Then the signals were filtered using fourth order Butterworth filter to remove noise. The frequency band chosen for the filter was 0.5Hz to 20Hz. Each segment of time series was windowed and tapered with a Tukey window. Power spectral density (PSD) of the filtered signals was estimated using Welch´s algorithm. Figure 2 shows the plot of estimated PSD of the twenty segments with mean PSD for both channels. Figures 2a, 2c, and 2e show plots of PSD from first floor to third floor in the direction of channel 1 with estimated mean PSD. Similarly, Figures 2b, 2d, and 2f show plots of PSD from first floor to third floor in the direction of channel 2. All plots show clear peaks which represents the fundamental frequency of the system in the corresponding direction.

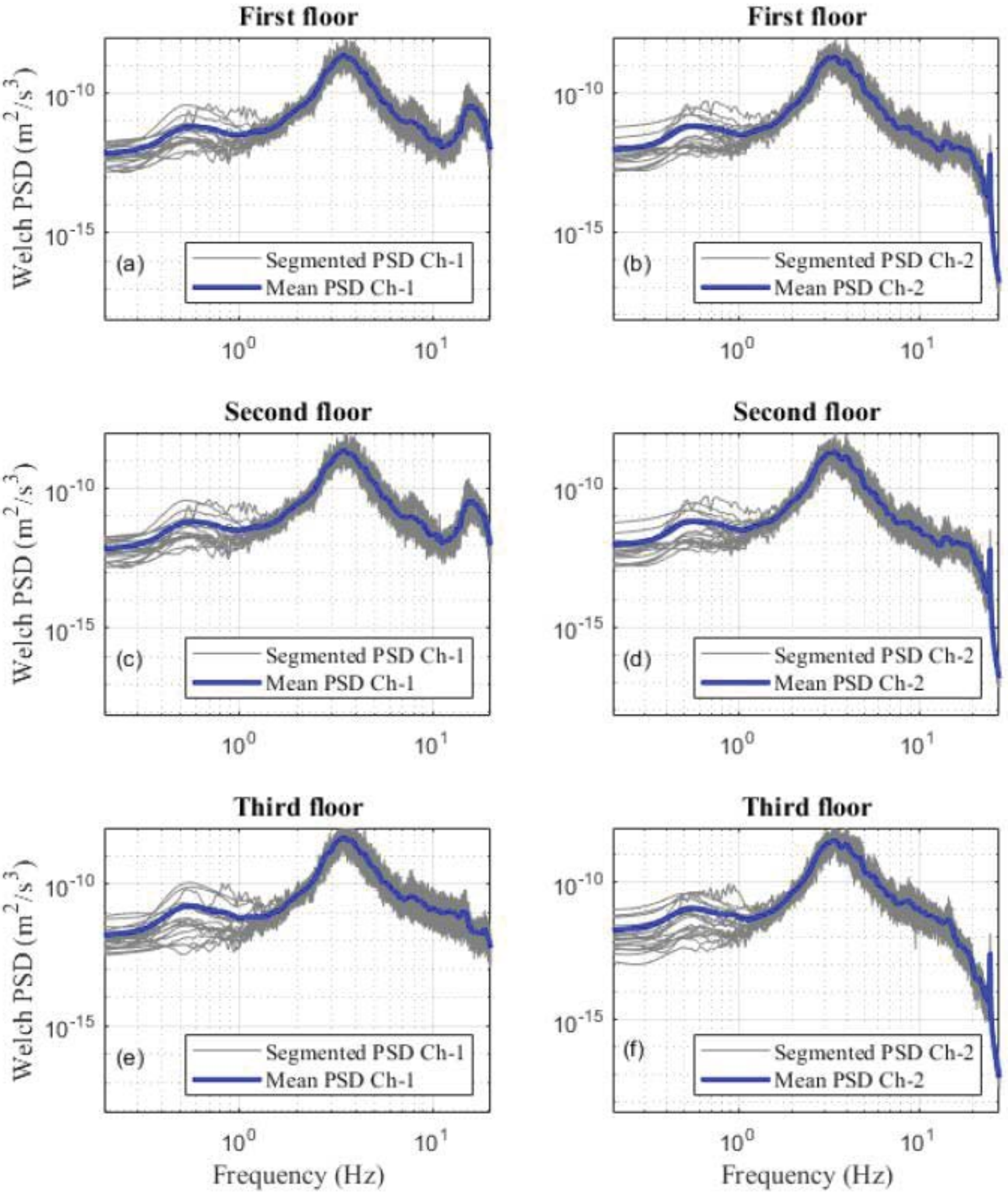

Figure 2: Plot of Welch´s PSD from recorded ambient vibration. The gray lines represent 20 segments of measured acceleration, and the blue lines represent the mean.

Estimated fundamental vibration period and damping ratios from three different floors are tabulated in Table 1. For example, mean vibration period estimated from channel 1 of the first-floor data is 0.290s with standard deviation 0.017s. Similarly, fundamental vibration period obtained from channel 2 is 0.289s with standard deviation 0.028s. Mean natural periods obtained from the second floor and third floor along channel 1 are 0.288s and 0.289s respectively. Mean natural periods obtained from second floor and third floor along channel 2 are 0.296s and 0.291s, respectively. Estimated vibration periods on both principal directions show consistently similar results for different floors. Mean of estimated vibration period along each direction represents fundamental vibration period of the building along corresponding principal direction. Therefore, it can be concluded that the mean estimated fundamental period of the building along channel 1 is 0.289s and along channel 2 is 0.292s. This concludes that the fundamental periods of the building on both the directions are almost similar. However, mean damping ratios estimated for both the channels from different floors shows more variability with higher standard deviations (range of variation 3 - 6%). Such variation on damping ratio is directly related to the smoothing, window selection and overlap of data during PSD estimation. For example, Smoothing of PSD leads to flattening of the peaks which results in inaccurate estimates of damping ratios [5].

Data	**Damping Ratio Ch-1 (%)**	**Fundamental Period Ch-1 (s)**	**Damping Ratio Ch-2 (%)**	**Fundamental Period Ch-2 (s)**
First floor	8.126 (3.681)	0.290 (0.017)	11.435 (4.939)	0.289 (0.028)
Second floor	8.389 (3.901)	0.288 (0.017)	9.165 (4.713)	0.296 (0.023)
Third floor	9.148 (4.303)	0.289 (0.016)	11.655 (6.211)	0.291 (0.027)

Table 1: Mean fundamental vibration period and damping ratio with standard deviation estimated from three different floors using Welch spectral analysis.

3.3 N4SID method

N4SID stands for Numerical algorithms for subspace state space system identification and is described in detail in [7]. This method is based on parametric mathematical model called state-space model which consist of a set of input, output and state variables linked together by first order differential equations. The following equations represent a state-space model in continuous time:

$$\left\{\dot{x}(t)\right\} = [A]\{x(t)\} + \{B\}u(t)$$
$$\{y(t)\} = \{C\}\{x(t)\} \tag{3}$$

Where [A] is parametric system matrix, {B} and {C} are parametric vectors. The vector {x(t)} is called the state of the structure. The number of elements of x(t), n, is called the model order. The state space model ([A], {B} and {C}) can be calibrated from measured excitation and response. The model can then be used to estimate vibration periods and damping ratios of the structure. The results are generally sensitive to the selected model order. Selection of suitable model number helps to remove spurious modes and bias of the modes. Spurious modes are either noise modes, that arise due to physical reasons, e.g., excitation and noise or mathematical modes that arise due to over-estimation of the model order. Similarly, bias of the modes can be defined as the combination of different modes (true mode and noise mode) on identified mode which is due to under estimation of model order. The selection of suitable model order is facilitated by stabilization diagrams. A stabilization diagram is made by selecting a wide range of model orders and by plotting all identified modes in a frequency versus model order diagram. Figure 2 shows the stabilization diagram for data segment 5 for channel 1. The plot shows the estimated natural frequencies and damping ratios for model orders 1 to 20. The parameters are estimated by the least squares rational function (LSRF) algorithm. The figure helps to identify stable and unstable peaks in the frequency response function. The results show that some of the true modes only appear after model order 4. A model order of 6 seems sufficient to identify the two modes of vibration of the structure, and is therefore selected for further analysis.

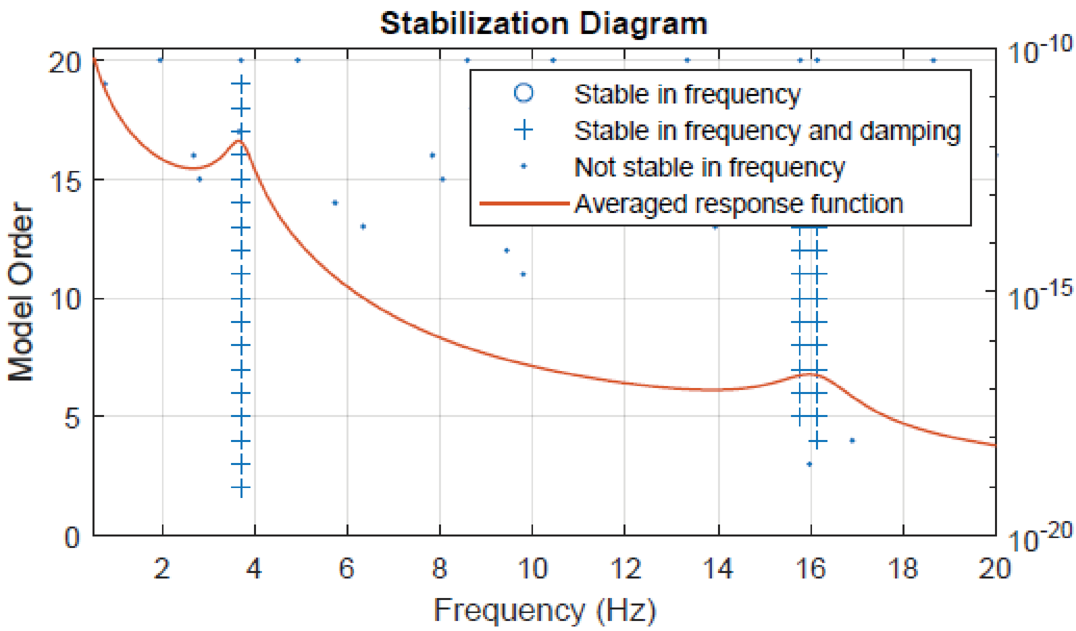

Figure 2: Stabilization diagram showing stable modes and averaged frequency response function for data segment 5 channel -1.

Measured signals from all three floors were aligned in time and divided into twenty segments. Signals were filtered using fourth order Butterworth filter The frequency band chosen for the filter was 0.5Hz to 20Hz. Then N4SID algorithm in MATLAB was used to estimate state-space model with model order of six. No exogeneous input was used in calibrating the model as the excitation is assumed to be a white noise process. Estimated mean fundamental vibration period and damping ratios are presented in Table 2. The mean vibration period for first and second mode obtained from channel 1 data is 0.266s and 0.078s with standard deviation of 0.009s and 0.031s. Similarly, the mean vibration period for first and second mode obtained from channel 2 data is 0.264s and 0.143s with standard deviation of 0.012s and 0.035s respectively. This shows that the variance of period obtained for second mode is higher than that for the first mode. Mean damping ratio obtained from channel 1 data is about 6.3% with standard deviation of 1.3%. Similarly, mean damping ratio obtained from channel 2 data is about 6.9% and standard deviation of 1.1%. Variation in damping ratio estimated from this method is lower than that estimated from the non-parametric method.

Data	Fundamental Period (s)		Damping Ratio (%)
	Mode 1	Mode 2	
Channel 1	0.266 (0.009)	0.078 (0.031)	6.340 (1.265)
Channel 2	0.264 (0.012)	0.143 (0.035)	6.968 (1.140)

Table 2: Mean fundamental vibration period and damping ratio with standard deviation estimated from ambient vibration measurement using N4SID method.

4 DISCUSSION AND CONCLUSIONS

The estimated fundamental period of vibration of the building is around 0.26s. The empirical equation proposed by Guler et al. [1] estimates the fundamental period of reinforced concrete moment resisting frames with brick infill walls with the following equation.

$$T_0 = 0.026H^{0.9} \tag{4}$$

For the building being studied here, this equation results in fundamental vibration period of 0.24s, which is fairly close to the results obtained from system identification. The building being studied is constructed on a site with alluvial deposits, which might affect the vibration frequencies of the structure. Dhakal, 2020 [11] presents finite element models of the building with fixed base and flexible base to account for the effects of soft soils at the site. The finite element models show that the vibration frequencies estimated from the flexible base model matches the results of system identification better. This indicates that system identification using ambient vibration measurement can be used to detect and calibrate the effects of underlying soil in vibration properties of buildings. This is valuable in calibrating and updating finite element models which can be used for detailed seismic analysis. For example, mechanical elements used to model soil in the finite element model of the building can be tuned to match the modal frequencies estimated from ambient vibration measurements.

The results of this study show that system identification using ambient vibrations is a reliable method of estimating the fundamental period of vibration of buildings. The estimated periods are consistent with results presented in the literature and mechanical models of the building. The parametric method seems to be superior to the non-parametric method and is found to be more reliable in identifying higher modes of vibration. In addition, damping ratios estimated from the non-parametric method showed larger variability than those estimated from the parametric method. The degree if smoothing used in the former method is subjective to the analyst and introduces such variability. There is no quantitative guideline on what degree of smoothing is optimal. In the parametric method, some level of subjectivity is introduced by the selection of model order. But unlike in the non-parametric method, the analyst can make use of the stabilization diagram to select a proper model order. In this aspect, the parametric method is found to be more suitable for system identification.

Since ambient vibration measurements are inexpensive and can be performed rapidly, it will be useful to perform similar tests on several buildings in Nepal. By sampling buildings of different construction quality, site conditions, heights, infill walls and opening ratios, effects of these parameters on vibration frequencies of typical reinforced buildings in Nepal can be studied. Furthermore, empirical equations relating these frequencies to parameters such as building height, site conditions, and opening ratios can be calibrated. Such equations will be useful in updating seismic design codes in Nepal.

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