DYNAMIC CHARACTERISTICS OF LEANING TOWER OF PISA USING MICROTREMOR
- PRELIMINARY RESULTS -

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ABSTRACT

Determining the dynamic characteristics in advance and increasing durability of ground and structures beyond the presumed seismic force is a fundamental for preserving the historical structures. Main purpose of this study is to investigate the dynamic and other characteristic features of Pisa tower and answer the questions such as in which frequency the tower vibrates and where is the center and direction of this movement? Microtremor method is applied for this purpose. Rocking vibration frequency for entire structure is found as 0.98Hz in NS and 1.06Hz for EW direction. Center of this movement in NS direction is located in rather southern site of the central axis, almost under the bottom of foundation. In EW side this depth is about 1.5m under the foundation. Amplification is bigger in EW direction which shows tendency to move to this direction also. Ground bearing capacity is also calculated and it has been found that it changes between 1kg/cm3 to 1.3 kg/cm3 for the vertical frequency changing between 2.2-2.5 Hz. From the results, microtremor method is proved to be a useful tool for this kind of investigations, since it easily gives needed information in a short period of time.

Key Words : Leaning tower of Pisa, Microtremor, Dynamic characteristics, H/V(QTS) spectrum, Rocking vibration, Spring coefficient (kv).

1. Introduction

Preservation of monuments all around the world and increasing their stability against destructive forces, especially to the earthquakes is an important issue for many countries. It is well known that, degree of damage during earthquakes strongly depends on dynamic characteristics of buildings as well as amplification of seismic waves. Because of this, first it is necessary to analyze their behaviors before reinforcing or repairing them.

Since historical monuments are not suitable for sophisticated analysis, strategy for this should be selected carefully. Considering this, the dynamic characteristics and response of the leaning tower of Pisa are analyzed on the basis of microtremor measurements, performed on the ground and upper floors of the tower.

The leaning tower of Pisa, has been tilting since 12th century . According to its history, tower has never really been straight. During its construction architects and later engineers have attempted to stop the leaning and lessen the angle. All these efforts had unintended side effects, and caused disastrous problems than they set to solve. Also many research on explaining the influences including soil condition of the ground and weather conditions have performed. However, the real danger for the safety of the Pisa is the possibility of earthquakes and there is no detailed study about the dynamic structural behavior of the tower which will be directly related with its damage during the earthquakes.

Among the other time consuming and expensive approaches, microtremor is the easiest and cheapest way to understand the structural behaviors without causing any harm to the structure. In a short period of time it provides several information including natural frequency, amplification and vibration characteristics of structures at different frequencies. Preliminary analysis of the measurements resulted that rocking vibration frequency is of 0.98Hz in NS and 1.06Hz in EW direction. Center of this movement is almost under the bottom of the foundation in NS direction located at southern side of the tower and at 1.5m depth at EW direction.

2. Information About the Leaning Tower of Pisa

The 14.000 tones, 58m high eight-story leaning tower of Pisa is one of the most original works of art of the European Middle-Age and there are lots of uncertainties about the original architect. It was started to built in the year of 1173 and completed at 1350. After a short time of construction started, tower started to incline toward the north. And nearly after 100 year,

the building shifted again so that by 1272, it was visibly leaning to the south. It stands more than 800 years daring to the gravity and today the top of the tower is about 5.227 meters off centers, tilting southward. Tower has 19.6 meters diameter with a foundation depth little less than 3 meters. Under the tower the components of the earth are mainly soil, clay and mud. The area where Pisa is located had been a port in medieval times and the soil is a spongy mixture. The surface layer (about 10 m) which is an accumulated fluvium from River Arno has compacted unevenly making the tower tilted. Under this layer, there is a resistant band known as Pancone marine clay with fine sand and shells which is about 20 meters deep. This is followed by a deep layer of sand boundary which is horizontal under most of Pisa, except where it is under the tower. Layers of clay and sand alternate down to roughly 70 meters. The entire area where the tower is built is gradually sinking.

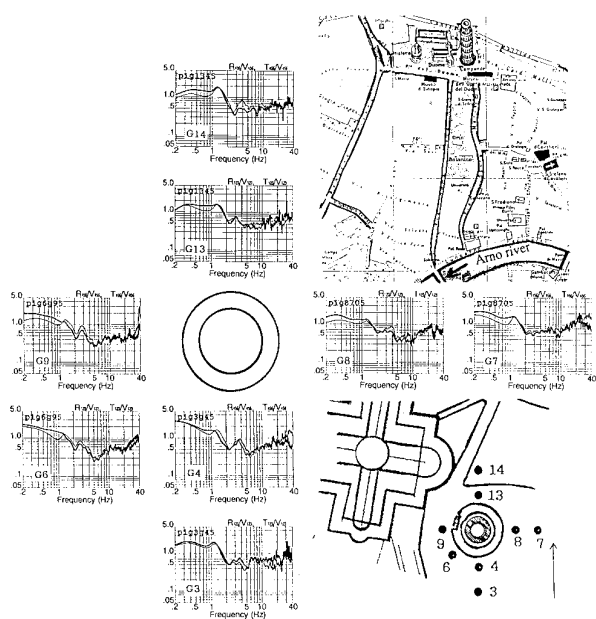## 3. Measurement Points and Outline of Measurement Conditions

Figure 1. Location of the tower and measurement points on the ground surface. Spectrums at right upper and left lower corner are QTS spectrums for ground surface points.

Figure 1. shows the area where the tower is located and position of the measurement points on the ground surface. Also QTS spectrums for ground surface measurements are included in this figure. Figure 2. shows cross section of the tower in NS direction, including measurement points on the structure and local geology under the tower. Rocking center depths for each floor are pointed with x.

(1) Measurement: An instrument named Portable Intelligent Collector (PIC) was used for microtremor

measurements. PIC includes two sensors, connection cables, main body installed in a metal case which contains A/D converter, portable computer and amplifiers inside. At every measurement points, three components (two horizontal and one vertical) of microtremor on the ground are recorded. Sampling interval is 1/100 sec and the length of each record is 40.96 sec. Measurement was repeated three times at each observation point. One set of PIC instrument together with two sensors was set on the ground floor while the other was moved from one floor to the other. With this system, microtremors of the tower and ground were recorded at the same time. Measurements were performed at 1P, 2P, 3P, 4P, 5P and 6P levels of tower shown in Figure 2.
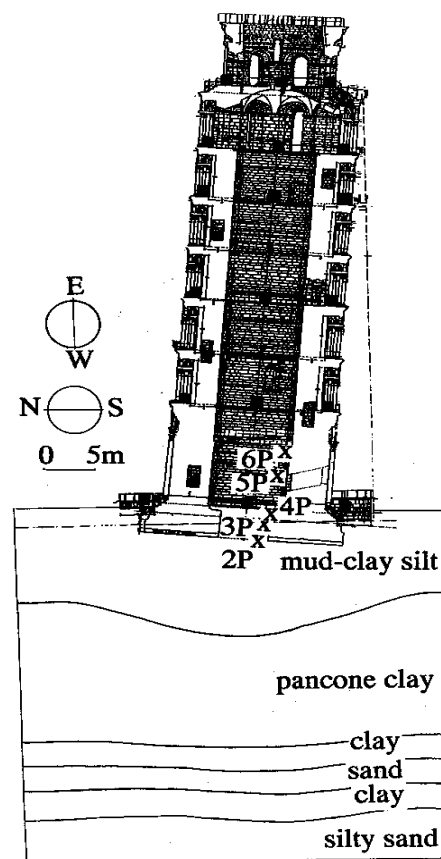

Figure 2. Cross section of tower in NS direction including measurement points on tower and local geological conditions. Rocking center depths for each floor is marked with x.

(2) Analysis: After measurements, Fourier spectrum for each components and QTS spectrums are calculated(Nakamura, 1989). From a spectral ratio of horizontal to vertical components QTS (Quasi Transfer Spectrum), predominant frequency (f) and amplification factor (A) which represents dynamic characteristics of the ground and spectral ratios between each floor and ground floor were calculated. This ratio provided the combined predominant frequency and amplification factor of entire tower and ground. Using a methodology introduced by

Nakamura et al.(1995) rocking and other vibration frequencies, together with rocking vibrations center depths are calculated for each floors.

4. Results

QTS spectrums of ground are given in Figure 1. It can be followed that having an amplification factor of 1.2 G6 and G8 have no clear peak probably because of the effects of structure of tower, as well as different ground characteristics at these points. Natural frequency is around 1.2 Hz at all the points. Amplification is rather high at G3, G4, G13 and G14 having a value of about 1.7 at longitudinal (NS) and transversal (EW) direction.
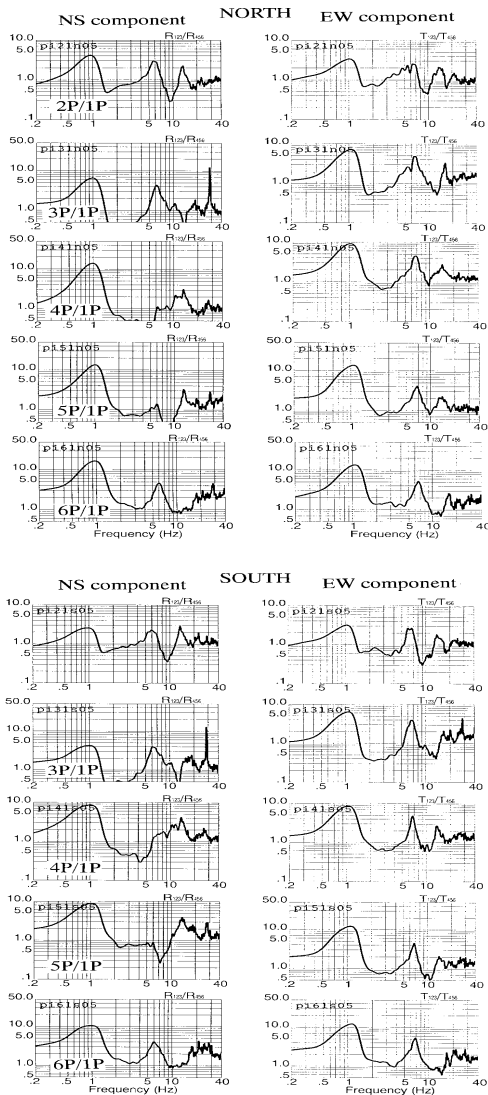

Figure 3a. Spectral ratios in NS direction.

Figure 3a and 3b shows spectral ratios of 2P, 3P, 4P, 5P and 6P with 1P. This ratio provided the combined predominant frequency and amplification factor of entire tower together with ground. There are several peaks showing the different modes of the structure in longitudinal and transversal components. First mode frequency is about 0.98Hz in NS and 1.06Hz for EW

direction. These shows the rocking vibration frequency of the tower. One reason of higher frequency in EW direction thought to be the weight of 830 tons of lead that is placed on the south of the tower. This weight cause a small amount of difference in inertial force in NS direction that might cause just a negligible difference in momentums which will almost have no effect in frequencies. The only reason seems to be a softer ground characteristics in NS direction. Vibration frequencies of the structure for the second and third mode are 6.3Hz and 14Hz, respectively. Figure 4, shows first mode vibration characteristics in NS and EW directions. In EW direction, amplification is higher than NS direction, this shows that tower has a tendency to move in EW direction also. Especially from 5P level this difference become bigger. This might be because of change in floor characteristics starting from this floor. Rocking center depth for each floor was also obtained from the spectrum ratio of the horizontal movements measured by two sensor fixed at the same floor .
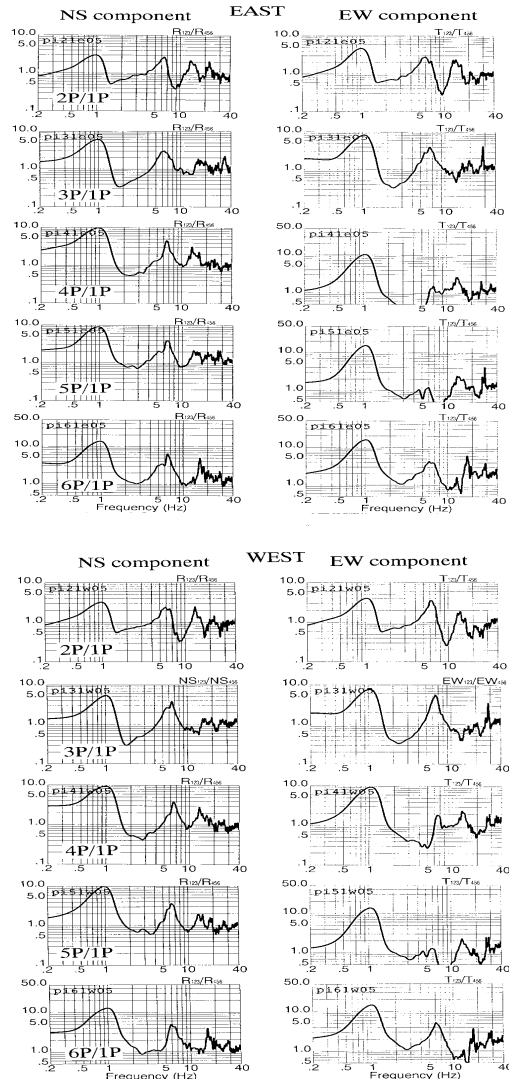

Figure 3b. Spectral ratios in EW direction.

Although having a deeper rocking center is better, center of rocking vibration found from present

measurement is quite shallow in NS direction(almost bottom of the foundation) located at the south of central axis. In EW direction this center is about 1.5m. Change of the location of the rocking depth in NS and EW direction is given on Figure 6.
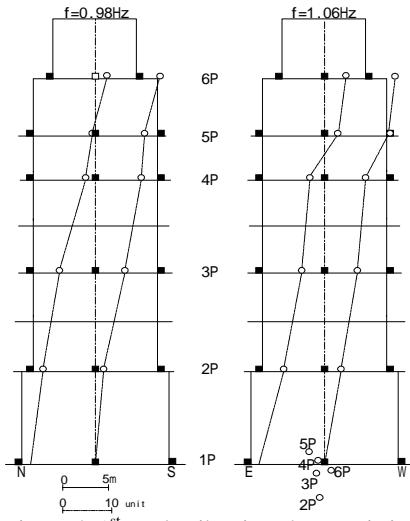

Figure 4. 1st mode vibration characteristics and location of rocking center depths in EW direction.
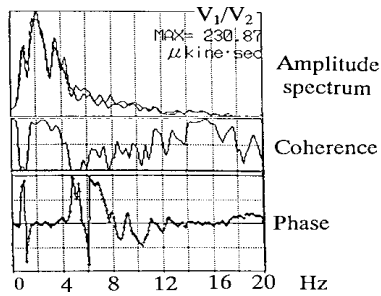

Figure 5. Ratio of vertical movements for 5P level (5P$_{east}$/5P$_{west}$)

Vertical vibration frequency for entire tower is also checked from the ratio of vertical movement for the same floors. Figure 5, shows an example for 5P$_{east}$/5P$_{west}$ ratio of vertical movements at 5P level. Amplitude spectrum, coherency and phase of these records are given. A peak at 1Hz represents rocking vibration. And a peak around 2 Hz appears at each floor shows a vertical vibration frequency for entire tower. Clear identification of vertical vibration frequency is quite important since it gives an opportunity to calculate spring coefficient kv that will be helpful to calculate ground bearing capacity. Normally investigation of this coefficient needs time consuming and expensive experiments. On the other hand, with the investigation of vertical vibration frequency this can be easily calculated with the following formulation.

$$\frac{Kv \cdot g}{W} = w^2 \rightarrow Kv = \frac{W \cdot w^2}{g}$$

$$Kv = A \cdot kv \rightarrow kv = \frac{W \cdot w^2}{g \cdot A}$$

Where Kv is ground bearing capacity, w=2πf. f is the vertical vibration frequency. W is the mass and g is gravity. By inserting the values for Pisa tower into this formulation which are, W=14000+820(lead) tons, A=294m^2, g=980 , f=2.2-2.5Hz, we can find the value for Kv changes between 1.0-1.3 kg/cm^3 for 2.2Hz and 2.5Hz vertical vibration frequencies, respectively. This represents the bearing capacity of soft ground that Pisa is located.
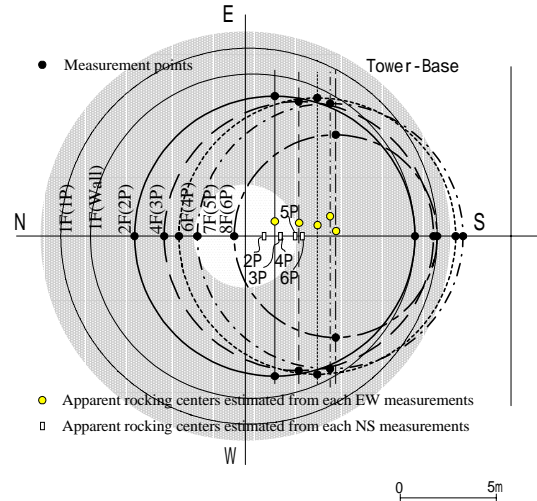

Figure 6. Bird eye view of floors showing rocking center locations on NS and EW directions at different floors.

5. Concluding Remarks

Dynamic characteristics of the Pisa tower are investigated as follows;

1) Predominant frequency and amplification factor of the ground is f=1.2 Hz and A=1.7. **2)** Rocking vibration frequency is 0.98Hz in NS direction and 1,06 Hz in EW direction. Center of this vibration is located at the south of center line almost under the bottom of foundation in NS direction. This depth is about 1.5m in EW direction. **3)** Vertical vibration frequency for entire tower is 3Hz. **4)** Bearing capacity has been calculated as 1-1.3 kg/cm3 for the area that tower is located. **5)** It has been shown that it is possible to investigate the response characteristics and structural damage of structures through the analysis of microtremor records. In later analysis other vibration frequencies are planned to be calculated from these information.

6. Acknowledgement

7. References

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