Monitoring the changes of dynamic characteristics of a high-rise building

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Abstract. To assess changes in the dynamic characteristics of the 25-storeyed building of the Kazakhstan Hotel in Almaty, an analysis of instrumental records of the station of engineering seismometric service was carried out. The building is located near the tectonic fault. During two earthquakes, representative instrumental data were obtained at the Seismic Station No. 16 (“High-rise Hotel”), equipped with digital instrumentation and measurement system. The building is twenty-five-storeyed with a stiffening core, built in 1976. Using the ADXL accelerometers and the RSM-32 recorder, high-quality instrumental records of accelerations were obtained in the basement, on the floors and on the roof of the building, and spectral curves were also built. The peculiar features of the dynamics of the specified building are noted during earthquakes. Periods of the building oscillation on the main and second modes of oscillation were revealed on exposure to a remote earthquake. Comparison of the dynamic characteristics of the house was carried out according to the measurements of 1977 and 2018. It has been established that there is a significant increase in the magnitude of the oscillation period on the first form by 25–48% as compared to the measurements of 1976–1977 over the 40-year period of operation.

1. Introduction

The issue of assessing changes in the dynamic characteristics of buildings over a long period of operation or the estimated service life of a structure is quite understudied. It is known that over a long-term period of building operation change in dynamic characteristics can be very significant. It is related to the fact that change in the groundwater table, repeated soaking of the basement part of the building, foundation soil compaction under heavy dead load, damage accumulation in the load-bearing structures of the building under repeated exposure to weak but sensible earthquakes, change in stiffness properties due to numerous re-layout of premises is feasible.

The problem is especially critical for high-rise buildings having heavy weight. Around one hundred houses from 18 to 38 floors in height were built in earthquake-prone areas of the Republic of Kazakhstan and in the city of Almaty. Therefore, the issue of change in the dynamic characteristics of such houses is very relevant for the specified territories and the city.[1-3].

The high-rise building of the Kazakhstan hotel was chosen to study this issue. The building is located near the tectonic fault.
2. Object of researches

The Kazakhstan Hotel, the first 25-storeyed high-rise building in a 9-point seismic zone of the former USSR, was built in 1976 in Alma-Ata (now Almaty). To date the building has been being operated for 42 years. The owners of the building changed many times. There has been numerous architectural re-planning of apartment floors of the building.

The design of the hotel was developed by the institute "Kazgorstroyproekt" with the participation of the scientific department of the institute "KazpromstroyNIIproekt". The number of stories in the building was established at the suggestions of Academician T. Zh. Zhunusov.

The hotel building has a height of 105.7 m and is an elliptically contoured core in plan view with dimensions of 12–44 m in axes.

The thickness of the core throughout the height of the building is constant and equal to 500 mm. In the radial axis, reinforced concrete membranes, monolithically connected with the core and having tapered thickness of 250-500 mm throughout the height of the building, extend away from the core. At the free end these membranes have a forked (V-shaped) section for the reinforced concrete to take the edge stresses and for ease of fixing the exterior foam plastic panels encased in a metal frame. Intermediate floors are made of cast-in-situ and partially pre-cast & cast-in-place reinforced concrete with effective thickness of 150 mm. Spatial system: the core-membrane-floors is embedded in a solid foundation plate made of cast-in-situ reinforced concrete with dimensions of 60.0x40.0x2.8 m, buried 10 m below the ground level. The reinforced concrete core was concreted using sliding formwork lifted by hydraulic jacks. Radial membranes and partially the floors were concreted in the travelling formwork, which had the sizes of the room and were installed two floors behind the sliding formwork [1-3].

Foundation slab with dimensions of 60.0x40.0x2.8 m is buried 10 m below the ground level.

The design model in the form of an elastic bar, having shear rigidity and flexural stiffness that are constant along the whole length corresponds to the dimensions of the building. The weight after the load summary is equal to \( Q = 52240 \) t (Figure 1).

![Figure 1. Computational model](image-url)
Solid homogeneous soils - boulders and pebble gravel with the layers of sand serve as a footing of the building. Characteristic strength of the soil is $R_n = 6.0 \text{ kgf/cm}^2$.

Seismic station No. 16 “High-rise Hotel” of the engineering seismometric service of KazNIISA JSC was installed in 1977. The station was upgraded in 2009. Digital recorder RSM-32 with accelerometers ADXL-500 is installed. Highly-sensitive sensors ADXL-1000 are installed on the 6th floor.

To analyze the dynamic behavior of the building, two types of seismic events (earthquakes) are considered. It should be noted that these earthquakes are quite slightly spread out over a period of time. It allows excluding the influence of any extraneous factors on the assessment of the dynamic characteristics of the building.

3. Local earthquake

According to information from the Data Center of the Institute of Geophysical Research (IGR), on February 02, 2018 at 15:20 p.m. (Astana time) (at 09:20 a.m. GMT) an earthquake took place in the city of Almaty. Coordinates of the epicenter: Latitude 43.15°N, Longitude 76.88°E. Magnitude $mb = 3.6$. Energy class $K = 7.5$. The earthquake was felt in Almaty with an intensity of 3-4 points. The earthquake focus was located in the Nauryzbay district of the city, i.e. directly in the territory of the city. The focal depth is insignificant. It is a typical local earthquake in the urban area, which occur every month in the last half year and, in principle, were observed earlier [6–8]. According to the database of instrumental data, it is the 98th earthquake.

4. Remote earthquake

According to quick-look data of the Data Center of RSE IGR (Institute of Geophysical Research) on August 9, 2017 at 05:27 a.m. (Astan time) (on the 08th of August at 23:27 GMT) in the border area of China (Xinjiang Uygur Autonomous Region), 100 km away from Dostyk settlement, 360 km away from Taldykorgan, 480 km away from Almaty, an earthquake occurred. Coordinates of the epicenter: Latitude 44.44°N, Longitude 82.92°E. Magnitude $Mw = 6.3$. The earthquake was felt in Almaty, in Taldykorgan – 4 points.

According to various sources, the depth of the earthquake source is 15-30 km.

Remote earthquake - the strongest recorded earthquake in Almaty in 2017. According to the database of instrumental data, it is the 96th earthquake.

5. Results and discussion

Both earthquakes were recorded by almost all stations of the engineering seismometric service of KazNIISA JSC. Instrumental records of the earthquake turned out to be very interesting. Accelerograms in two axes on horizontal plane were obtained at all registration points. Sampling interval of accelerograms is 0.0064 s.

Tables 1 and 2 show the maximum acceleration magnitudes for each of the components of instrumental records. Spectral curves were determined by integrating the differential equation of the classical single-mass oscillator using the solvers of the computer mathematics system SCILAB. Solution method is automatically selected between the non-stiff predictor-corrector Adams method and the stiff Backward Differentiation Formula (BDF) method. Initially, a non-stiff method is applied and then the data is dynamically checked in order to decide which method to be used.

The decrement of oscillation in the determination of spectral curves is assumed to be 5% of the critical value.
Table 1. Maximum acceleration values and accelerogram parameters of local earthquake

| №  | Constituent       | Acceleration, cm/s² | Effective duration, s | Spectral factor | Peak period of spectrum, s |
|----|-------------------|---------------------|-----------------------|-----------------|----------------------------|
| 1  | 98-16-26x-OX      | 24th floor          | 10.50                 | 0.56            | 2.82                       | 0.20                       |
| 2  | 98-16-26y-OY      | 24th floor          | 11.73                 | 0.13            | 2.21                       | 0.10                       |
| 3  | 98-16-26z-OZ      | 24th floor          | 10.41                 | 2.32            | 3.81                       | 0.17                       |
| 4  | 98-16-21x-OX      | 21st floor          | 8.50                  | 0.54            | 4.66                       | 0.17                       |
| 5  | 98-16-21y-OY      | 21st floor          | 12.47                 | 0.13            | 2.96                       | 0.10                       |
| 6  | 98-16-18x-OX      | 18th floor          | 11.32                 | 0.34            | 2.99                       | 0.20                       |
| 7  | 98-16-18y-OY      | 8th floor           | 9.22                  | 0.31            | 3.06                       | 0.10                       |
| 8  | 98-16-6x-OX       | 6th floor           | 0.33                  | 0.21            | 4.07                       | 0.10                       |
| 9  | 98-16-6y-OY       | 6th floor           | 0.33                  | 0.92            | 4.02                       | 0.20                       |
| 10 | 98-16-2x-OX       | 2nd floor           | 0.28                  | 1.05            | 3.61                       | 0.20                       |
| 11 | 98-16-2y-OY       | 2nd floor           | 0.36                  | 0.04            | 2.50                       | 0.09                       |
| 12 | 98-16-xpod-OX     | basement            | 0.24                  | 0.12            | 2.48                       | 0.13                       |
| 13 | 98-16-ypod-OY     | basement            | 0.02                  | 52.56           | 2.78                       | 0.10                       |

Table 2. Maximum acceleration values and accelerogram parameters of remote earthquake

| №  | Constituent       | Acceleration, cm/s² | Effective duration, s | Spectral factor | Peak period of spectrum, s |
|----|-------------------|---------------------|-----------------------|-----------------|----------------------------|
| 1  | 96-16-u3-OX       | 24th floor          | 25.20                 | 25.20           | 5.30(4.02)                 | 1.45(0.39)                 |
| 2  | 96-16-u4-OY       | 24th floor          | 23.62                 | 50.43           | 464(4.59)                  | 1.09(0.32)                 |
| 3  | 96-16-u5-OX       | 21st floor          | 14.23                 | 54.37           | 7.03                       | 1.45                       |
| 4  | 96-16-u6-OY       | 21st floor          | 12.48                 | 57.47           | 7.17                       | 1.09                       |
| 5  | 96-16-u7-OX       | 18th floor          | 15.20                 | 28.93           | 5.44(4.04)                 | 1.45(0.38)                 |
| 6  | 96-16-u8-OY       | 18th floor          | 13.41                 | 89.81           | 5.48(4.01)                 | 1.09(0.32)                 |
| 7  | 96-16-u11-OX      | 2nd floor           | 0.244                 | 29.38           | 5.85                       | 0.39                       |
| 8  | 96-16-u12-OY      | 2nd floor           | 0.239                 | 34.16           | 4.54                       | 0.32                       |
| 9  | 96-16-u13-OX      | basement            | 0.192                 | 50.55           | 4.85                       | 0.40                       |
| 10 | 96-16-u14-OY      | basement            | 0.032                 | 117.69          | 2.89                       | 0.32                       |
| 11 | 96-16-u15-OX      | 6th floor           | 0.341                 | 32.07           | 5.23(2.36)                 | 0.32(1.11)                 |
| 12 | 96-16-u16-OY      | 6th floor           | 0.352                 | 27.16           | 6.29(1.18)                 | 0.39(1.09)                 |

5.1 Local earthquake

Analysis of table 1 shows an insignificant effective duration of exposure. The duration of the oscillation with a magnitude of more than half of the amplitude is no more than 1 second (except for
2 registration points). Therefore, the impact of local earthquake is in the nature of a short pulse. Any significant resonance phenomena do not have time to appear. The peak period of the spectrum from Table 1 does not characterize the building’s own dynamic characteristics.

The greatest values of acceleration from the 18th to the 24th floor are 9-12.5 cm / s². In the basement level along the axis OX, acceleration is order of magnitude higher than along the axis OY.

The maximum values of the spectrum peak are located in the high-frequency area - the predominant period of oscillation is 0.1–0.2 sec (Fig. 2). For a sufficiently flexible building, the effects of this sort are not dangerous.

5.2 Remote earthquake

In table 2, in the levels from the 18th to 24th floor, the accelerations along orthogonal axes differ quite a bit - 7-10%. Accelerations in the level of the 24th floor are 2 times higher than under the influence of a local earthquake.

It should be noted that at small acceleration magnitudes in the basement and 2nd floor levels, the accelerations in the level of the 21st, 25th floors increase by 3 orders of magnitude. There is an increase in oscillation amplitudes towards the upper part of the building. The oscillations of the building are resonance in nature.

The effective length of accelerograms throughout the height of the building exceeds the similar characteristics during local earthquake by 50-100 times. This explains the significant effect on people living in the upper floors of high-rise buildings.

By the acceleration amplitudes, the intensity of ground shaking in the area of the seismic station is approximately four-point.

Figure 3 shows the spectral curves for both horizontal axes in the levels of the registration points from Table 2.

High-frequency vibrations prevail in both directions in the levels of the basement and the 2nd floor. Starting from the 6th floor, the spectral curves are mainly double-humped, nested into each other. Moreover, this regular pattern is sustainable. The characteristic of the period of oscillations is an inherent characteristic of the dynamic model of a building with a period of oscillation. In essence, there are resonance phenomena.

If for a local earthquake, the oscillations are of an uneven impulsive in nature with a small effective duration, then for a remote earthquake there are pronounced resonance phenomena (Fig. 2-3) that allow to reveal the dynamic characteristics of the building. The peak period of the spectrum for a remote earthquake can be identified as the period of oscillation by the basic tone of the building.

The magnitudes of the prevailing periods differ in two axes. Along the axis OX, the period of oscillations by the basic tone is about 1.45 s, along the axis OY - 1.1 sec.

Earlier, after the erection of the hotel building in 1977, the dynamic tests were carried out using resonant vibration machine of inertial action B-3 and by the blow of suspended load.

Vibration tests were preceded by the recording of free vibrations of a building caused by the impact of suspended load. Resonance tests were carried out in eight stages, during which inertial loads were applied in incremental steps.

According to the data from paper [4], during the tests in 1977:

- The estimated value of the period of free oscillations on the first basic tone along the transverse axis is 1.55 seconds, on the second - 0.25 seconds. Design characteristics were taken according to the scheme in Fig.1.
- The period of free oscillations caused by the impact of a suspended load is 1.1 seconds in the transverse direction and 0.74 seconds in the longitudinal direction.
- Resonance frequency according to vibration tests leads to a period of oscillations of 1.05-1.11 sec.

It should be noted that considerable discrepancy between the design and actual oscillation periods, especially on the first form, is due to the fact that by the time of the test the weight of the structure...
was much less than the estimated one due to the lack of useful loads, the weight of equipment, components of finishing and protective coats, floors, etc.

Thus, the differences in the period of free oscillations according to the results of 1977 and 2017 are 25% in the transverse direction and 48% in the longitudinal direction. We can fix the change in the oscillation period of the Kazakhstan hotel building over the 40 years of operation. To be more exact, the "building-soil" system, due, for example, to soil compaction under the foundation slab of the building.

It is also interesting that the magnitude of the oscillation period on the basic tone in 2018 approached to its calculated value. The difference is now less than 10%.

![Spectral curves of seismic event on 02.02.2018](image1.png)  
**Figure 2.** Spectral curves of seismic event on 02.02.2018

![Spectral curves of seismic event on 09.08.2017](image2.png)  
**Figure 3.** Spectral curves of seismic event on 09.08.2017

Thus, by selecting the instrumental records of earthquakes that occurred, it is possible to trace the change of the oscillation period during the service life of the building. It bears reminding that the results were obtained when exposed to a remote earthquake in the territory of China. The results of the work can be used to predict the behavior of a 25-storeyed Kazakhstan hotel located near tectonic faults during expected earthquakes.
6. Conclusion

1. Over the service life of the building of 42 years, there is a change in the dynamic characteristics (oscillation period) by 25-48% as compared to the measurements in 1976-1977.
2. The periods of 1.45 seconds and 0.40 seconds are periods of oscillations on the first and second forms of building oscillations in the transverse direction. In the longitudinal direction along the axis OY, the period of free oscillations is 1.1 seconds.
3. The maximum magnitudes of accelerations in the levels of the basement and 21-25 floors of the building differ by 2 orders of magnitude when exposed to a remote earthquake.
4. Seismic event (earthquake in China - Xinjiang Uygur Autonomous Region) on August 9, 2017 in the territory of Almaty in the area of Seismic station No. 16 “High-rise hotel” is an earthquake with an intensity of at least 3-4 points.
5. Local earthquakes do not lead to resonance phenomena for the 25-storeyed Kazakhstan hotel building.

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