Vertical Shaking Accident and Cause Investigation of 39-story Office Building

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Abstract
At around 10 a.m. on July 5, 2011, a building shaking occurred at Techno Mart 21 located in Guui-dong, Seoul, for 10 to 15 minutes, resulting in emergency evacuation of the residents. Because this building is a 39-story building, evacuation from the upper floors took a long time. In the initial phase of the accident, the building structure was determined to be safe through an emergency safety evaluation conducted by the Korea Infrastructure Safety Corporation operated by the Korean government. Such social anxiety was further amplified by speculative reports released to the press regarding footing settlement, wind-induced vibration and climate-induced vibration prior to a review of the vibration source by an expert group. Thus, the need to discover the vibration source and to present a solution was suggested.

The purpose of the study was to conduct an initial investigation on the vibration source, identify the exact cause of the vibration through an investigation into the predicted vibration source and structural analysis, and establish the appropriate measures to prevent recurrence of such accidents.

Keywords: shaking accident; building structure; vibration; vibration source; investigation

1. Introduction
1.1 Summary of Accident
At around 10 a.m. on July 5, 2011, a building shaking occurred¹ at Techno Mart 21 located in Guui-dong, Seoul, for 10 to 15 minutes, resulting in emergency evacuation of the tenants. Because this building is a 39-story building, evacuation from the upper floors took a long time. It has been reported that it took over an hour for people on the upper floors to evacuate during the 9/11 terrorist attack, and thus, the issue of risks related to evacuating from high-rise buildings is a sensitive matter for tenants. Also, due to the history of approximately 500 deaths during the collapse² of Sampoong Department Store in 1995, Koreans react more sensitively toward building accidents and this has emerged as a major social issue. In the initial phase of the accident, the building structure was determined to be safe through an emergency safety evaluation conducted by the Korea Infrastructure Safety Corporation operated by the Korean government. However, the fact that the vibration source remains unknown has led to greater anxiety and concerns among building tenants and users, resulting in a reduced number of people shopping at the shopping mall and subsequent decline in the revenue of the merchants. Such social anxiety was further amplified by speculative reports released to the press regarding footing settlement, wind-induced vibration and climate-induced vibration prior to a review of the vibration source by an expert group. Thus, the need to discover the vibration source and to present a solution was suggested.

The purpose of the study was to conduct an initial investigation on the vibration source, identify the exact cause of the vibration through an investigation into the predicted vibration source and structural analysis, and establish the appropriate measures to prevent recurrence of such accidents.

1.2 Summary of Building
An overview of the building at which the abnormal vibration accident occurred is shown in Table 1.

| Category            | Description                  |
|---------------------|------------------------------|
| Building Scale      | 6 under and 39 ground floors,|
| Structure           | Steel structure +           |
|                     | steel-reinforced concrete structure |
| Construction        | August 18, 1998              |
| Elapsed Years       | Approx. 13 years             |
| Main Uses           | Office, shopping, performing arts and sports facilities |
| Max. Height         | 188.7m                       |

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2. Investigation into the Vibration Accident
2.1 Vibration Accident and Description
This section describes the accident and the actions taken between the date of vibration occurrence, July 5, and August 11, 2011. Details are given on the 1st vibration accident, on which the initial report was made to the National Emergency Management Agency, the actions taken by the local government, prevention center and building operation department, the sudden collapse of the ceiling, and the 2nd vibration accident that occurred approximately one month following the initial report.

1) 1st Vibration Accident
A constant vibration occurred at Techno Mart building situated in Guui-dong, Gwangjin-gu, Seoul, for 10 to 15 minutes from 10:10 a.m. on July 5, 2011, and a report was received by the National Emergency Management Agency. The Agency conducted an emergency evacuation of the building tenants at 2 p.m., and convened experts in architectural structures for a meeting to establish countermeasures. At the meeting, they resolved to perform an emergency safety evaluation of the building, which was commissioned to the Korea Infrastructure Safety Corporation, which specializes in the safety evaluation of large-scale structures.

The results of the safety evaluation showed that the structural members and foundation of the building did not cause the abnormal vibration and based on these results, the relevant experts initially concluded that it was a resonance effect caused by abnormal vibration. However, the cause of the abnormal vibration remained unknown, and this led to the decision to perform an investigation to trace the precise cause.

2) Ceiling Collapse
After the 1st vibration accident, there was a sudden drop of the ceiling finishing material on the 10th floor of the commercial tower on August 3, 2011, and the event was reported to the National Emergency Management Agency by the tenants. The relevant administrative department convened the experts who took part in the investigation into the 1st vibration accident to perform a field survey. Based on the results of the field survey, it was confirmed that a regular safety inspection had been performed to inspect the ceiling interior prior to this incident. In particular, the footprints of safety inspectors and traces of damage were found on the ceiling, which had fallen, and from this, it was confirmed that this incident was not caused by vibration.

3) 2nd Vibration Accident
Around the time of conclusion of the 1st vibration accident investigation, vibration similar to the 1st vibration accident occurred for 1 to 2 minutes at around 11 a.m. on August 11. This incident was again reported by the tenants to the National Emergency Management Agency. The experts partaking in the 1st vibration accident investigation were summoned for a meeting. This incident occurred at a phase where the experts were identifying the cause of the initial accident and planning a demonstration of the accident, and it increased their confidence in the results of the initial investigation.

2.2 Speculated Source of Vibration
Researchers could not accurately understand the situation at which the vibration accident occurred. Thus, they presented possible vibration sources to be analyzed and reproduced to deduce the vibration source. The possible vibration sources presented by the researchers included wind load, air conditioning control room mechanical vibration, footing settlement and structural crack; the details are shown in Fig.1.

1) Wind load: occurrence of vertical vibration caused by factors such as eddy resulting from wind blowing against the structure
2) Air conditioning control room mechanical vibration: resonance phenomenon due to mechanical vibration caused by air conditioning equipment in the air conditioning control room situated on each floor of the office tower of Techno Mart
3) Fitness center on the 12th floor of the office tower: structural vibration caused by the resonance phenomenon of vibration due to spinning, treadmill, group rhythmic exercise, etc., at the fitness center
4) 4D theaters of CGV on the 9th floor of the commercial tower: structural vibration caused by the resonance phenomenon of vibration due to equipment for 4D screening
In addition, issues of footing settlement and loss of foundation caused by heavy rainfall the previous day were suggested, but during a field visit, it was determined that such phenomena did not occur and cannot cause such vibration. Thus, an analysis of the four possible causes stated above was conducted.

3. Review of the Design Documents

3.1 General Details

Design documents of Techno-mart 21 building must contain clear information necessary for production and installation of structures such as the size and location of each member, center of column, dimensions of the ribbed parts, size and number of bolts, welding size, and other details. Thus, in order to understand the current status and information regarding the building, determine whether it was designed in accordance with the design documents, and use the information in the safety evaluation, this section describes the results of the review of the design and structural calculation documents.

3.2 Main Contents of Structural Drawing

1) Steel was used to manufacture all the beams and columns of the office tower. Moment frame was designed for the long span direction and braced frame for the short span direction, with the core wall being a shear truss wall. They were designed as a dual frame system, resistant to wind and seismic loads.

2) The steel form deck plate slab system was applied to the 2nd floor and above, whereas the reinforced concrete slab system was applied to the 1st floor and below.

3) The beams and columns of the underground floors of the office tower were all made of steel.

4) As for the underground floors of the shopping mall, SRC was used for the column, steel for the beams of the 1st and 2nd underground floors, and reinforced concrete for the beams of the 3rd to 5th underground floors.

5) A reinforced concrete structure was applied to the exterior retaining wall of the underground floors.

6) As for the foundation, individual footing was used for the shopping mall and mat foundation for the office tower.

7) Granite was in-filled with a 600 mm slab on the top, and was designed to have the predicted inflow of water yard-drained at the sump-pit.

8) The steel columns of the office tower were designed as box columns up to the 13th ground floor. The external columns in the long span direction (excluding the core) on the 14th floor and above were designed as box columns, while other columns were designed as the H-type.

9) The span of the office tower frame structure (excluding the core) was mainly 10.2 m and 7.5 m in the short span direction and 7.2 m in the long span direction.

3.3 Review of Design Documents

The results of the review of the building design documents can be summarized as follows:

1) The results of the review of the design drawing and reports confirmed that all information was accurately provided in the design documents.

2) It was confirmed that the structural design met the standards of KBC-1996.

3) The member and joint details described in the structural calculation sheet and the member and details indicated in the design drawing were found to be consistent.

4) The review of the design documents confirmed that the design of the building satisfied the structural design standards, and the results of the structural analysis showed that there were no problems in terms of stress.

4. Prediction of Vibration Source

4.1 General Details

On-site measurement and demonstration were performed as shown in Fig.2. on the speculated vibration sources, which include wind load, mechanical vibration from the air conditioning control room, fitness center and 4D theaters, in order to identify the vibration source. The details are as follows:
4.2 Prediction and Reproduction of Vibration Source

4.2.1 Vibration Caused by Wind Load

The Korea Meteorological Administration\(^9\) provides the public with constant measurements of wind speed at a unit of cell. According to the data, the wind strength at the time of the vibration accident was gentler than usual, based on which it was determined that there was no reason for any larger vibrations caused by the wind load than usual. However, vibration caused by wind load is most common and there were many experts who predicted that the vibration accident was caused by wind load. Thus, a decision was made to measure the vibration of the building in the event of high-strength wind such as a typhoon near the building.

High-strength wind caused by typhoon Muifa was expected 40 days after the accident, during which the building vibration was measured. The results showed that no one felt any vibration at this time, and the upper part of the building was not shown to be amplified due to vibration.

4.2.2 Mechanical Vibration of 4D-Theater

The building contains 4D theaters, which produce mechanical vibration during the movement of the seats to present a more realistic experience to the audience during movie screenings. However, the vibration accident occurred prior to the screening of 4D movies, and the vibration of the seats occurred 30 minutes after the start of the movie. Based on these results, it was determined that the mechanical vibration of the 4D theaters did not have an impact on the vibration, which occurred at around 10 am.

4.2.3 Group Rhythmic Exercise at Gym

There is a wide range of exercise programs available at the fitness center concerned, and diverse forms of vibration can occur depending on the location of the people inside. Thus, it was checked whether the size of acceleration and vibration caused by the group rhythmic exercise (Taebo), etc., that can periodically produce strong or constant vibration on the floor could be transmitted to the 22nd, 26th, 30th and 34th floors. In particular, because the 26th floor contains empty offices and has no reason for unusual vibrations, it is where the resonance phenomenon has the highest possibility of occurrence in case the external load matches the natural frequency of the building.

1) Experiment on Vibration Excitation by Humans

In order to perform verification with respect to the 2.7Hz frequency, which was slightly amplified with the operation of the treadmills, a vibration excitation experiment was carried out in the G.X. room using a metronome and the vibration transmission and amplification were checked.

Vibration Excitation and Measurement Plan

Fig.3. and Fig.4. show the view of the G.X. Room of the fitness center on the 12th floor where the vibration excitation experiment was carried out.

![Fig.3. 12th Floor Plan (Fitness Center)](image)

![Fig.4. Vibration Excitation by Humans in the G.X. Room of the Fitness Center on the 12th Floor](image)

![Fig.5. Time History and FFT Analysis of Vibration Excitation on the 12th Floor](image)
acceleration responses of the floor slabs were taken on
the 12th floor as shown in Fig.5.

2) Results of Experimental Measurement

The experimental results of the time history analysis
of acceleration and frequency analysis conducted at the
upper part of the building are shown in Fig.6.

As shown in Fig.6., acceleration increased after a
certain period of time, unlike the two types of measured
Taebo exercise programs, and this tendency was shown
on all measured floors. Also, the amplification of the
acceleration response was more prominent on the upper
floors, confirming that the frequency of the vibration
excitation (2.7Hz) was a frequency that amplified the
vibration in the vertical direction.

The amplification of the acceleration response is
more clearly shown in Fig.7. and Fig.8., which are
the result of the frequency analysis. As shown in the
figure, the amplification ratio of a particular number of
vibrations seen in the result of the frequency analysis
of spinning and treadmill was greater during vibration
excitation by humans, and it was confirmed that the
higher the floor, the higher the amplification ratio.

Table 3. and Table 4. show a comparison of the
maximum values and RMS of the acceleration response
of the 12th and 34th floors. As shown in Table 3., in
the case of the RMS response, the acceleration of the
floor on which vibration excitation was performed was
high, with low distribution of the response on the 34th
floor but higher than the response caused by spinning
or treadmill operation.

Table 3. Comparison of the Accelerations During Group
Exercise (RMS)

| Location             | Measurements | 1st (gal) | 2nd (gal) | 3rd (gal) | Note (avg.) |
|----------------------|--------------|----------|----------|----------|------------|
| 12th floor (office   | 14.89        | 21.13    | 15.55    | 17.19    |
| tower)               |              |          |          |          |            |
| 34th floor (office   | 0.37         | 0.99     | 1.06     | 0.81     |
| tower)               |              |          |          |          |            |

Table 4. Comparison of the Accelerations Using Group
Exercise (Peak)

| Location             | Measurements | 1st (gal) | 2nd (gal) | 3rd (gal) | Note (avg.) |
|----------------------|--------------|----------|----------|----------|------------|
| 12th floor (office   | 145.64       | 155.81   | 168.55   | 156.67   |
| tower)               |              |          |          |          |            |
| 34th floor (office   | 2.70         | 6.90     | 6.62     | 5.41     |
| tower)               |              |          |          |          |            |

4.2.4 Vibration Caused by the Mechanical Room
and the Wind

The existing equipment in the air conditioning
control room is in continuous operation. Thus, there
was no reason to think of it as a new vibration source.
The various machines in the mechanical room produce
vibrations at a significantly higher frequency than
the natural vibration frequency of the building, and
thus it was determined that there was no relation between the mechanical vibration produced by the air conditioning control room and the vibration accident. Also, the wind load at the time of the vibration accident was confirmed to be low as shown in the table from the meteorological data provided by the Korea Meteorological Administration.

4.3 Resonance Phenomenon

All matter has its own unique movement, and the characteristics of the movement are mathematically noted as natural frequency and natural period. The resonance phenomenon occurs when the natural vibration frequency of a matter equals the vibration frequency of an external force. In the case of general vibration, reduction of vibration occurs away from the epicenter, whereas in the event of resonance, vibration becomes stronger away from the epicenter. Such phenomenon can be understood based on the dynamic amplification factor that occurs in the structure as shown in [Eq. 1].

[Eq. 1] represents the displacement amplification factor according to the vibration frequency of the external force and the vibration frequency of the structure, and the vibration frequency ratio based on this is shown in Fig.9. This equation shows that when the natural vibration frequencies of the external force and the structure match (fp/fn=1), the displacement response is amplified almost infinitely, and such amplification effect is referred to as the resonance phenomenon.

However, due to the damping effect that interferes with the movement in actual structures and objects, the ratio of amplification decreases depending on the strength as a solid line in Fig.8. (damping 1.0%) and infinite amplification does not occur in actuality. The collapses of the Angers Bridge in France (1850), Tacoma Bridge in Washington in the U.S. (1940), and the Millennium Bridge are famous for being caused by the resonance phenomenon; these accidents occurred due to the amplified displacement of the structure resulting from the vibration frequency of pedestrians or the wind load matching the natural vibration frequency of the structure.

\[
D = \max \left| \frac{u(t)}{u_{\text{static}}} \right| = \frac{1}{\sqrt{1-(f_p/f_n)^2}^2+\left[2\pi(f_p/f_n)^2\right]^2} \quad \text{[Eq. 1]}
\]

The case of this building is very unusual in that resonance occurred in the longitudinal direction of the structure due to a group rhythmic exercise of humans, and the amplification of displacement was too small to have an impact on the safety of the building, yet it caused discomfort to the users of the building.

The resonance phenomenon does not only have negative impacts, but has been very useful in real life. For instance, switching to a certain radio or TV channel concentrates the external frequency signal concerned to cause resonance with the receiver and allow users to receive the broadcast.

5. Conclusion

Measurement/demonstration of the predicted vibration sources, which include the fitness center, 4D theaters, wind load and mechanical vibration, were performed and the wind-induced vibration was measured. The acceleration responses of each of the vibration sources were reviewed based on the measurements, and the results are as follows:

(1) As for the fitness center on the 12th floor of the office tower, the on-site measurements and demonstration with respect to the group rhythmic exercise, spinning and running on the treadmill, which were regarded as the possible sources of vibration at the time of the vibration accident, showed that spinning and running on the treadmill did not have an impact on the vibration on the upper floors of the building. Also, exercises such as Taebo did have frequency characteristics transmitted to the upper floors, but did not amplify the vibration.

(2) In the case of repetitive rhythmic exercise at 2.7Hz, which is the vertical vibration mode of the building, the frequency characteristics are transmitted to the upper floors, with the amplification of acceleration increasing at higher floors. Repetitive rhythmic exercise performed by a group can cause resonance and increase the vibration level, and was determined to be the source of the vibration that occurred on July 5, 2011.
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