Evaluation of Noise Insulation Performance for Void Deck Slab System which Combines Deck Plates with a Voided Slab System

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Abstract
A voided slab system is one of the newly developed methods used to improve the load resistance by effectively utilising the moment of inertia in a concrete slab. It has several advantages such as economic efficiency, usability, and environmental friendliness. In this study, the authors developed a new voided slab system, called a void deck slab (VDS) system, which is combined with voided slab systems and deck plates. The purpose of this study is to investigate the sound insulation performance of VDS. To determine its effectiveness, a mock up test was carried out to evaluate its insulation performance against floor impact noise and its applicability to a voided slab system. The test results show that the light impact sound insulation performance reached grade 1, and the heavy impact sound insulation performance reached grade 3. These results satisfy the required impact sound insulation performance of apartment housing. Based on these results, it is expected that the application of VDS can be useful in preventing interlayer noise issues in apartment housing in South Korea. In addition, it is thought that a reduction of in the quantity of concrete required will not only improve the workability in construction sites, it will also reduce the emissions of carbon dioxide. Thus, VDS will be a useful alternative method to improving the habitability for occupants and the workability for workers at construction sites.

Keywords: voided slab; deck plate; noise insulation performance; interlayer noise issue; apartment housing; light impact noise

INTRODUCTION
A voided slab system is one of the newly developed methods used to improve the load resistance by effectively utilising the moment of inertia in a concrete slab. It has several advantages such as economic efficiency, usability, and environmental friendliness. In contrast, it also has certain disadvantages in that construction difficulties on site are higher than with normal reinforced concrete slabs despite the decrease in the quantity of concrete and reinforcing bars. In addition, the economic efficiency is worse in that extra construction costs are incurred when the voided part is not properly constructed. To overcome such difficulties of a voided slab, a number of new methods have been developed. Voided slab systems have been actively applied to buildings and are being continuously used in many countries including those in Europe, Asia, North America, the Middle East, and Oceania. In particular, it has been proven that a voided slab system is beneficial in lowering the noise propagation and noise complaints between floors in apartment housing in Japan. In South Korea, voided slab systems with steel pipes have been applied to the Grand Hyatt hotel and several different warehouses. The system has since been gradually applied to large buildings and long-span structures such as underground parking structures, office buildings, factories, cinemas, and religious facilities. In addition, it is being investigated whether the utilisation of a voided slab system can solve social issues such as noise complaints and floor impact noises caused by footsteps in apartment housing, which occupies the majority of domestic dwelling types.

Noise insulation from indoor and outdoor-generated noises in apartments is a significant factor in improving the quality of life and comfort of residents. One of the most frequently generated noise issues amongst occupants in apartment housing in South Korea is noise complaints that occur between upstairs and downstairs neighbours (i.e., interlayer noise problems). Because such noise complaints have become a serious social issue, a number of efforts and technologies have been proposed to resolve the problem. Interlayer noise is a type of floor impact noise, and is the most important aspect of residents of apartment dwellings in evaluating the comfort and indoor noise level. To reduce the interlayer noise problem, it is necessary to assess the level of impact of sound insulation from slabs applied in a building structure. It has been reported that the former materials used in voided slabs have an outstanding performance in terms of sound insulation against floor impact sounds. In this study, the authors developed a new voided slab system, called a void deck slab (VDS) system, which is combined with voided slab systems and deck plates. The purpose of this study is to investigate the sound insulation performance of VDS. To determine its effectiveness, a mock up test was carried out to evaluate its insulation performance against floor impact noise and its applicability to a voided slab system.
LITERATURE REVIEW

Voided slab or hollow core slab systems have been used for many years in the field of civil engineering in South Korea, where long span structures such as bridges and dams are frequently constructed. However, the application of voided slab systems in the architectural, engineering, and construction (AEC) industry occurred later in South Korea than in Europe or Japan. Although it is late compared to other countries, the design and construction of voided slab systems are now being carried out in the construction of various long-span buildings and large facilities in the AEC industry.

Research into voided slab systems in South Korea has focused on the development of anchoring methods and the shape of the void former materials. Various studies have proposed the use of new materials to anchor the void former materials into concrete slabs. The majority of studies regarding anchoring materials have focused on the use of reinforcing bars, which fix the anchoring materials to the lower reinforcement of the slab. The reasons for using anchoring materials have been to prevent buoyancy, which occurs during the placement and curing of concrete, as well as the movement of void former materials by workers during reinforcement tasks. Another research theme regarding voided slabs has been the development of new shapes of void former materials. The most significant factors in researching the shapes of void former materials has been attaining an optimal hollowness ratio that is able to distribute stress and demonstrating the best structural performance of voided slabs. Research on voided slabs in South Korea is summarised in Table 1.

A considerable amount of research into voided slabs has been studied and accumulated in Europe and Japan since the 1900s. In particular, a voided slab system has been proven to significantly reduce the interlayer and impact noises occurring in apartment dwellings, and has therefore been widely used in apartment houses in Japan. The main research trends toward the use of voided slabs in foreign countries have been similar to the topics in South Korea, which are the development of anchoring materials, and finding the optimal hollowness ratio. Such research trends can be confirmed through the number of patent applications and registrations (see Figure 1). As shown in Figure 1, the development of voided slabs has been progressing in Europe since 1974, and patent applications and registrations were continuously submitted between the mid-1980s to the mid-2000s in Japan. In the case of South Korea, the development of voided slab systems has rapidly increased since the mid-2000s. BubbleDeck Technology in Denmark and Cobiax Technologies AG in Switzerland have developed a voided slab system that lowers the amount of concrete required and therefore the weight of the slab by using spherical or elliptical plastic balls as lightweight void former materials for application in one- and two-way slabs. The main feature of Cobiax Technologies AG is to develop cages for fixing spherical or elliptical lightweight void formers to reinforcing bars to slabs. As a Japanese study, while Sekisui Plastics Co., Ltd., focused on the development of voided slabs using half precast concrete in the 1980s, in recent years the company has been researching new technologies to prevent the detachment or separation of void formers from slabs. Moreover, various other companies in Japan such as Kurimoto, Penta Ocean, and Shimizu are trying to develop new materials to fix or anchor void former materials to a slab to secure their reliability and durability. Table 2 summarises recently proposed technologies and materials used in voided slabs in foreign countries and regions.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chung et al.</td>
<td>2009</td>
<td>An analytical study of hollow slabs with optimal hollow spherical shapes</td>
</tr>
<tr>
<td>Kim et al.</td>
<td>2009</td>
<td>Structural performance tests of two-way void slabs</td>
</tr>
<tr>
<td>Joo et al.</td>
<td>2011</td>
<td>Structural performance test on installation method of void former for void slab using deck plate</td>
</tr>
<tr>
<td>Lee et al.</td>
<td>2011</td>
<td>Experimental evaluation on punching shear of two-way void slab-to-column connection with TVS lightweight ball</td>
</tr>
<tr>
<td>Chung et al.</td>
<td>2013</td>
<td>Experimental study on the bond characteristics of deformed bar embedded in donut type biaxial hollow slab</td>
</tr>
</tbody>
</table>
Figure 1. Patents for voided slab technologies since 1974

Table 2. Voided slab systems used in foreign countries

<table>
<thead>
<tr>
<th>Nation/Region</th>
<th>The name of the system</th>
<th>Characteristics of the void formers</th>
<th>Weight reduction ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Materials</td>
<td>Weight</td>
</tr>
<tr>
<td>Europe</td>
<td>Cobiax</td>
<td>Plastic</td>
<td>1400 kg/m³</td>
</tr>
<tr>
<td></td>
<td>U-Boot system</td>
<td>Plastic</td>
<td>1400 kg/m³</td>
</tr>
<tr>
<td>USA</td>
<td>Fligree wide slab system</td>
<td>Plastic</td>
<td>1400 kg/m³</td>
</tr>
<tr>
<td>Japan</td>
<td>Momslab</td>
<td>Styrofoam</td>
<td>15–30 kg/m³</td>
</tr>
<tr>
<td></td>
<td>EJ void</td>
<td>Styrofoam</td>
<td>15–30 kg/m³</td>
</tr>
</tbody>
</table>

MATERIALS AND TEST METHODS

Void deck slab system

The void deck slab (VDS) system is a newly developed voided slab construction method that uses deck plates to anchor void formers. VDS has certain advantages including an improved constructability, easier installation, connection precision, and a reduction in the amount of concrete used in the slabs. In addition, VDS is environmentally friendly, including a reduction of CO₂ emissions, because the use of concrete in the slabs can be reduced as the void former materials are inserted.

The deck plates used for VDS not only serve as a concrete formwork, they also anchor the void former materials. Additionally, the deck plates operate as a part of the structural member, receiving additional structural strength and thereby increasing the structural stability. Figure 2 shows the details and a schematic view of VDS. VDS is composed of T-shaped steel deck plates, lightweight void former materials, and anchoring devices, as shown in Figure 2. As Figure 4 indicates, in the cross section of VDS, the lightweight void former materials are placed between the ribs of the T-shaped steel deck plates. The anchoring materials of the void former materials to deck plates would be the same as the void formers and they would be installed by inserting and turning them 90 degrees. Such ease of application makes it possible for novice workers to install and fix the void formers with a high level of precision and improved workability.
Test overview

Mock-up tests were carried out to evaluate the floor impact sound insulation of reinforced concrete slab using the VDS system. A three-bay two-storey building was constructed as a mock-up test specimen using VDS, as shown in Figure 3. The building used for the mock-up test has two floors of 4.8 m in width and 5.5 m in length. The concrete and reinforcing bars used for this specimen had a compressive strength of 24 MPa and tensile strength of 400 MPa.
The VDS floor was finished with gypsum panels, lightweight porous concrete, side insulation, and finishing mortar, as popularly utilised in apartment housing in South Korea (see Figure 5). The properties of the materials used in the mock-up test specimen are summarised in Tables 3 and 4. Figure 3 shows a placement illustration of the second floor and the cross section of the specimen building.

Table 3. Material properties of T-shaped deck plate

<table>
<thead>
<tr>
<th>Design strength (MPa)</th>
<th>W/C (%)</th>
<th>S/a (%)</th>
<th>Water (kg/m³)</th>
<th>Cement</th>
<th>Fine aggregate (kg/m³)</th>
<th>Coarse aggregate (kg/m³)</th>
<th>Admixture (kg/m³)</th>
<th>Air content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>49.4</td>
<td>47.5</td>
<td>162</td>
<td>328</td>
<td>882</td>
<td>993</td>
<td>1.64</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Floor impact test

Equipment used for the floor impact sound generation and measurement is shown in the Figure and Table. In this test, two types of sound generator for light and heavy impact sounds were used for generation of the floor impact sounds. In the case of the heavy impact sound generator (i.e., a bang machine), the tests were carried out at a tyre air pressure of \((2.4 \pm 0.1) \times 10^5\), which is the air pressure for a bang machine as regulated by the Korea Standard (KS).

The tests were conducted in accordance with KS F 2810-1:2001 (Field measurement of impact sound insulation of floors – Part 1: Method using standard light impact source) and KS F 2810 – 2: 2012 (Field measurement of impact sound insulation of floors – Part 2: Method using standard heavy impact source). The frequency range of the lightweight impact sound was 125, 250, 500, 1000, and 2000 Hz, and the heavy impact sound frequency range was measured using a 1/1 octave band of 63, 125, 250, and 500 Hz, respectively.
To calibrate the effect of the background noise, the background noise was measured for each frequency level before obtaining the noise data. When the level difference between the background and measured noise was 6 to 15 dB, the acquired data were compensated through the following expression.

$$L_{F_{\text{max}}} = 10 \log_{10} \left( \frac{L'_{F_{\text{max}}}}{10} - 10^{L_b/10} \right) \text{ (dB)}$$

Here, $L_{F_{\text{max}}}$ is the compensated maximum sound pressure level (dB), $L'_{F_{\text{max}}}$ indicates the measured maximum sound pressure level including the background, and $L_b$ represents the sound pressure level of the background noise.

The floor impact noise level $L$ of the sound receiving room, which indicates the floor impact sound isolation performance of the floor structure to be measured, was obtained according to the formula for each measured frequency.

$$L_{F_{\text{max}},k} = 10 \log_{10} \left( \frac{1}{m} \sum_{j=1}^{m} \frac{L_{F_{\text{max}},j}}{10} \right) \text{ (dB)}$$

Here, $L_{F_{\text{max}},j}$ is the maximum sound pressure level measured at point j, and m represents the number of measurement points.

In the case of a lightweight impact sound level, the sound absorption area of the receiver room was corrected through the following equation after the level of the normalised floor impact sound was measured.

$$L_n = L + 10 \log_{10} \frac{A}{A_0} \text{ (dB)}$$

Here, $A_0$ is 10 m$^2$, $A$ is equal to $\frac{0.16V}{T}$, $A$ is the area of absorption (m$^2$), $V$ is the volume of the receiver room, and $T$ is the reverberation time.

**Floor structures and measurement location of the sound**

The structures of the floor were composed using finishing mortar, an impact isolator, lightweight porous concrete, and a VDS slab, as shown in Figure 5. The floor impact sound was measured 0.75 m away from the wall, and four points including the centre of the floor were selected as the measurement location in the mock-up specimen. Microphones were used to obtain the impact sound data at a distance of 0.75 m from the wall, and at a height of 1.2 m from the floor. Figure 7 shows the floor plan of the mock-up test building, and the sound source and reception points.
Evaluation method of insulation performance for standard lightweight impact sources

The measured data were analysed based on KS F 2863-1:2002 (Rating of floor impact sound insulation for impact source in buildings and building element – Part 1: Floor impact sound insulation against standard light impact source) and KS F 2810-2:2012 (Field measurement of floor impact insulation of buildings – Part 2: Method using standard heavy impact sources).

<table>
<thead>
<tr>
<th>Grade</th>
<th>Inverse A normalised floor impact sound level (Lightweight floor impact noise)</th>
<th>Inverse A normalised floor impact sound level (Floor impact noise)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[L'_{n,AW} \leq 43]</td>
<td>[L'<em>{i,F</em>{max},AW} \leq 40]</td>
</tr>
<tr>
<td>2</td>
<td>[43 &lt; L'_{n,AW} \leq 48]</td>
<td>[40 &lt; L'<em>{i,F</em>{max},AW} \leq 43]</td>
</tr>
<tr>
<td>3</td>
<td>[48 &lt; L'_{n,AW} \leq 53]</td>
<td>[43 &lt; L'<em>{i,F</em>{max},AW} \leq 47]</td>
</tr>
<tr>
<td>4</td>
<td>[53 &lt; L'_{n,AW} \leq 58]</td>
<td>[47 &lt; L'<em>{i,F</em>{max},AW} \leq 50]</td>
</tr>
</tbody>
</table>

Table 5 shows the insulation performance rating criteria for light and heavy impact sounds. As indicated in Table 5, light and heavy impact sound sources of at least 58 and 50 dB are required, respectively, as a basis for the insulation performance of the floor impact sound of an interlayer floor.

Evaluation of the floor vibration

The walking load and heel impact load applied to the slabs of a building or structure cause unpleasant vibrations and stresses to the residents in a building or structure. To prevent such inconveniences in a building, domestic and international institutes and organisations have established regulations and standards to stipulate the performance level of the slabs. To corroborate the applicability and suitability of VDS for prevention of vibration insulation, it was necessary to test its floor vibration performance.

The method for evaluating the floor vibration performance in South Korea is stipulated in the KS and regulations. This evaluation method in South Korea has a number of difficulties when assessing the usability of slabs. First, the limit state design of steel and reinforced concrete structures applied by the KS were developed through an interpretation and citing of foreign standards and regulations rather than establishing Korean-specific rules. With these design guidelines, the vibration limit is only for the structural stability, rather than the usability of the occupants. Moreover, a usability evaluation exists regarding floor vibration in the design codes of...
composite slabs with a deck plate, and in the design specifications for cold-formed steel sections. However, the evaluation methods in these criteria limit the minimum natural frequency of the slabs, and thus it might be difficult to evaluate the usability in terms of the occupants or users being able to feel vibrations. Lastly, the Noise and Vibration Control Act in South Korea measures the damage level of a building or structure by defining the horizontal limits regardless of the frequency bands rather than an evaluation of the usability of the residents in the building.

On the other hand, the evaluation method of the vibration performance in other countries is divided into two evaluation criteria. The first is an evaluation method using an allowable limit of natural frequency. This method uses the modified Reiher-Meister curve, which applies the average value obtained from experience and actual experiments. The other is evaluated using the natural frequencies, damping ratios, and limit accelerations using evaluation or empirical formulas. In particular, ISO 2631-2 (1989), “Guidelines for evaluating residential performance on vibration of buildings,” by the Architectural Institute of Japan (AIJ), and DIN 4150-3 (1999) are guidelines for evaluating the direct habitability in which the residents will feel floor vibrations. In this study, the evaluation method proposed by AIJ was adopted to examine the usability and habitability of VDS.

The AIJ method for evaluating floor vibrations is based on analysing various standards such as ISO 2631-2, Reiher-Meister, GSA, and CSA, and a response curve in accordance with the Japanese design criteria was proposed. To assess the vibration using this evaluation method, the performance evaluation curves are divided into impact vibrations and continuous vibrations. To meet the criteria, the applied vibration is separated into heel drop and walking loads.

For the heel impact load on a slab, a person with a body weight of 700 N, chosen based on the existing references, lifted their heels 50 mm above the floor, and the vibration of the slab was measured when applying a free fall impact, as shown in Figure X. Additionally, the walking load was applied by a person 700 N in weight while watching a sensor placed in the centre of the floor while walking from a wall toward the centre point at a velocity of 2 Hz. Figure 8 shows the vibration measurement method on a slab and the equipment used in the experiment.

(a) Heel impact load
(b) Walking load

![Figure 8. Floor vibration loads](image)

### DATA ANALYSIS

**Results of floor impact sound**

Tables 6 and 7 show the results of light and heavy impact floor sounds applied in this study. The test results indicate that the performance of the light floor impact sound isolation reached grade 1 in all areas where VDS was applied. In addition, the heavy impact sound isolation performance was measured as grade 2 in one location in the mock-up test specimen, and grade 3 in two locations. The sound isolation performance was found to completely satisfy the minimum requirements of sound isolation, which should reach a mark of grade 3 or higher. Based on the results of these experiments, it is expected that the application of VDS into the slabs of apartment housing will be useful and effective with an excellent sound insulation performance.

![Table 6. Test results of walking load](image)

<table>
<thead>
<tr>
<th>Test</th>
<th>Natural frequency (Hz)</th>
<th>Maximum acceleration response (s/m²)</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.0</td>
<td>0.23</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>13.7</td>
<td>0.30</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>11.5</td>
<td>0.25</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 9. Results of heel impact and walking load tests
Figure 10. Natural frequency of heel impact
CONCLUSIONS

The purpose of this study was to investigate the applicability of a voided deck slab (VDS) system that can insulate the floor impact sounds and vibrations in apartment housing in South Korea. The test results show that the light impact sound insulation performance reached grade 1, and the heavy impact sound insulation performance reached grade 3. These results satisfy the required impact sound insulation performance of apartment housing. Based on these results, it is expected that the application of VDS can be useful in preventing interlayer noise issues in apartment housing in South Korea.

In addition, the vertical vibration performance of VDS was assessed based on the “Guidelines for evaluating residential performance on vibration of buildings” by AIJ. The results of the vertical vibration performance of VDS were measured as grade 1, which applies to the living room or bedrooms of apartment housing to insulate from annoying vibrations. However, when the length of the slab is longer than that used in the present research, and the size and the number of rooms are increased, the floor impact sound is expected to be measured as between grade 1 and grade 2. Thus, it is necessary to conduct additional experiments to investigate the effects of the number of rooms and the length of the span of the slabs on the sound insulation performance of VDS.

Finally, based on the results of this study, the application of VDS to apartment housing is considered a useful countermeasure to reduce disputes and discomfort caused by interlayer floor noise and vibrations in apartment housing in South Korea. In addition, it is thought that a reduction of the quantity of concrete required will not only improve the workability in construction sites, it will also reduce the emissions of carbon dioxide. Thus, VDS will be a useful alternative method to improving the habitability for occupants and the workability for workers at construction sites.

REFERENCES


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