Examples of Prediction and Countermeasures due to Human Rhythmic Action of Concert Audience

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Summary

In recent years, it has become a problem that vibrations occur in surrounding buildings due to human rhythmic actions of concert audience. For this difficult problem, it is necessary to take appropriate measures from the initial stage.

This report introduces issues and points regarding this vibration in the four steps of (1) prediction, (2) consensus building, (3) countermeasures, and (4) verification.

Keywords: human rhythmic action, live house, concert, environmental vibration, excitation force

1 Introduction

In recent years, there has been an increase in the number of cases where vibrations are generated in surrounding buildings due to the simultaneous movements of audience members in concert halls and live music venues, causing problems. The vibration source of this problem is the in-phase excitation motions of hundreds to tens of thousands of spectators that match the tempo of the music, and the overall excitation force applied to the structural floor and dirt floor is massive. The vibration generated by the excitation force propagates not only within the same building but also over a wide area through the ground, manifesting itself as an unpleasant bodily sensation vibration in the surrounding buildings.

The four steps of prediction, consensus building, countermeasures, and verification are important in dealing with vibrations caused by human movement during concert performances, as is the case with other environmental vibration problems. However, this problem has a wide range of effects, and countermeasures after the vibration problem are extremely difficult; hence more careful and appropriate handling is required from the design stage. This study focuses on the vibration problem during concert performances, and describes in detail the issues, key points, and examples of how to deal with the problem sequentially.

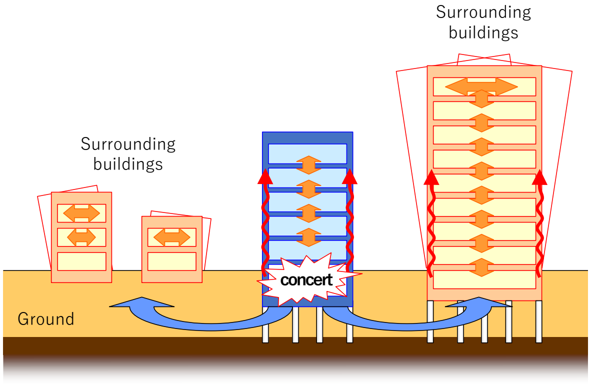

Fig.1　Mechanism of vibration caused by concert

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2 Prediction

2.1 Excitation force

A massive excitation force from hundreds to tens of thousands of spectators must be appropriately set to predict the vibrations during concert performances.

AIJ Recommendations for Loads on Buildings[1)], hereafter referred to as “the load guideline”, will likely be the first reference when a designer sets the excitation force. In the load guideline, a dynamic load factor α_n (i.e., F/W) is defined as the ratio of the excitation force F to the weight W of the persons who move with excitation frequency f and n-order harmonic component for each type of excitation, and values of α_1– α_3 are set. Table 1 shows α_1– α_3 for one-person jump landing, many people jump landing, and many people concerts extracted from the load guideline.

Next, we introduce previous research on jump landing and excitation force during concerts. We evaluated the excitation force using a force plate for eight types of movements during concerts, including jump landing, and classified the movements into (1)–(3) from the perspective of the magnitude and frequency characteristics of the excitation force[2)].

(1) Jump mode: jump landing motion in which the sole of the foot is off the ground.
(2) TATENORI action mode: repetitive movement of “standing on toes → landing on heels → light bending → standing on toes.”
(3) Bend and stretch mode: bending movement that creates a rhythm by bending and stretching the knees without lifting the heels.

Fig. 2 shows the excitation force for one-person movement among the three movement types, with movement (1) having the largest and movement (3) having the smallest excitation force. The figure shows that the result of one person jump landing agrees well with the result of the load guideline and that the excitation force changes depending on the movement and tempo of the song.

Table 1 Dynamic load coefficient due to human rhythmic action [1)]

	f(Hz)	α_1	α_2	α_3
One person jump landing	2.0～3.0	1.07～1.9	0.44～0.69	0.087～0.31
Multi-person jump landing	1.5～3.0	0.7～1.5	0.25～0.6	0.087～0.15
Multi-person cocert	1.5～3.0	0.25	0.1	0.025

The study conducted by Taguchi et al. is an example of published research on the excitation force when the excitation number of people increases[3)]. Excitation experiments were conducted on the floor of an existing building, and the excitation force for jumping movements of 1–48 people was obtained by substitution method. The results showed that the excitation force of 250 people was estimated up to a high order, with dynamic load factors of α_1: 0.84, α_2: 0.28, α_3: 0.04, α_4: 0.01, α_5: 0.007, and α_6: 0.006. When compared to Table 1, α_1 was 0.84 instead of 0.25, α_2 was 0.28 instead of 0.1, and α_3 was 0.04 instead of 0.025. This study suggests a risk of underestimating the excitation force when using many people concert values of the load guideline for the excitation force of approximately 250 people.

Previously, we also directly obtained the excitation forces α_1–α_6 of 1–16 people jump landing using a floating floor and investigated the relationship between the excitation number of people and α_n[4)].

Meanwhile, there are no published studies on the results of identifying the excitation force of thousands to tens of thousands of people, and designers rely on the above-mentioned research results and their own experience to set the excitation force used in predictive analysis after considering safety factors. Therefore, the proper setting of the excitation force is dependent on the designer's skill.

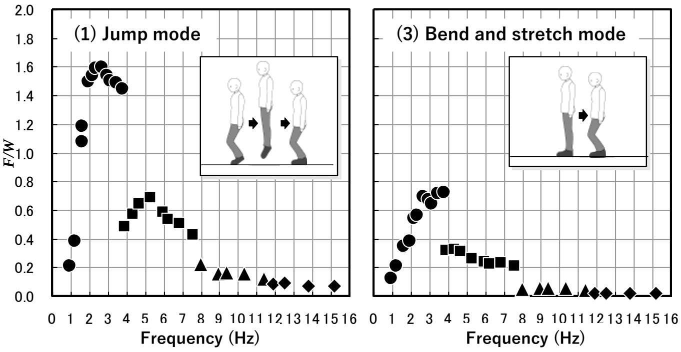

Fig.2 Relationship between *F*/*W* and frequency of jumping landing & bending

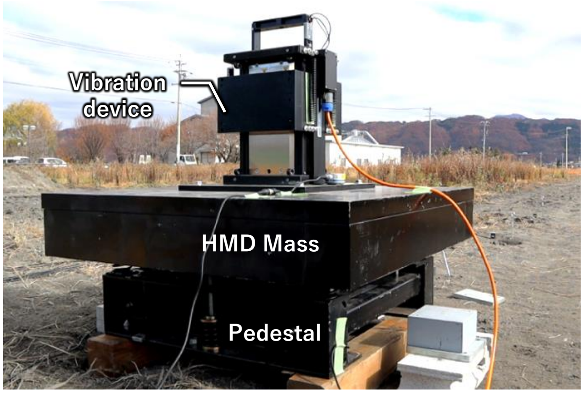

Photo 1 Hybrid mass damper for shaking the ground

Although the data cannot be disclosed due to project confidentiality, we have been investigating this massive excitation force for many years and have improved its accuracy. Specifically, we have used a hybrid mass damper (HMD) for shaking the ground with a 20-kN-class maximum excitation force shown in Photo 1 to accumulate data on the excitation force identified by measuring the vibrations that occur during many people excitation tests and actual concerts on the ground and in buildings, where the vibration characteristics in the frequency range of several Hz are grasped in detail. We will continue this effort and reflect it in the design of stadium and arena facilities.

2.2 Predictive analysis

Predictive simulation analysis is another opportunity to show the designer's skill. In the case of walking vibration, a single floor of a certain area is often a sufficient range of the analysis model; however, a larger analysis model needs to be created in the case of vibration during a concert performance that influences a wide area.

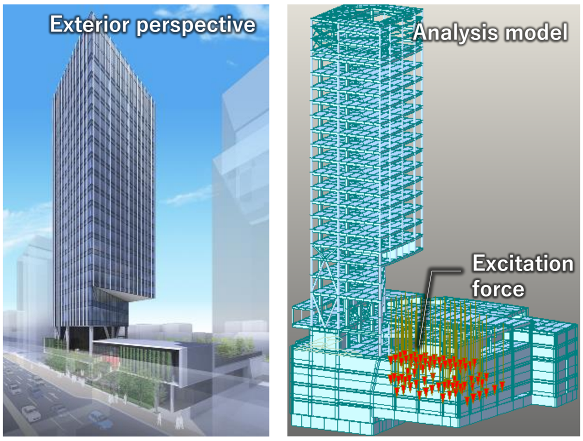

Fig.3 Exterior perspective and analytical model of the case building

Recently, the performance of computers has improved dramatically, and it has become possible to model entire complex buildings, including concert venues, and perform 3D FEM analysis. Herein, we introduce an analysis example of a complex building with 17 floors above ground and a concert venue with a capacity of 1,746 people (when standing) on the third basement floor. Please refer to a previous report5) for the details of this case.

Fig. 3 shows the exterior perspective and analysis model of the example building. The 5th–17th floors of the high-rise building are used as offices, and there is a 13-m protruding structure. There have been concerns since the start of the design that vibrations generated during concert performances would propagate to the high-rise building. Therefore, vibration countermeasures were planned, such as the reinforcement of rigidity by trussing the floor immediately above the protruding structure and the adoption of cast-in-place RC piles with high rigidity. The analysis model targeted the entire building, and in addition to these countermeasures, the rigidity of the ground and piles were also modeled as vertical springs. Based on prior experience, an excitation frequency component of 686.5 kN, the second harmonic component of 88.3 kN, and the third harmonic component of 9.8 kN were input to the floor of the concert venue on the third basement floor as the excitation force for the jump landing motion of 1,746 people.

As results of confirming the vertical and horizontal vibration modes of the high-rise building up to 10 Hz by eigenvalue analysis, it was expected that a maximum vertical vibration of 2.2 cm/s^2 (0-P) would occur in the 3.8-Hz vibration mode whose mode shape is shown in Fig. 4. The countermeasures taken for this predicted value are described later in Section 4.2.

The natural frequency and mode shape were confirmed by measurement when the building frame was completed. The predicted and measured natural frequency values were 3.8 Hz. For the mode shape as well, the measured amplitude agreed roughly with the predicted amplitude, where the value of the maximum modal amplitude was normalized to one, as shown in Fig. 4.

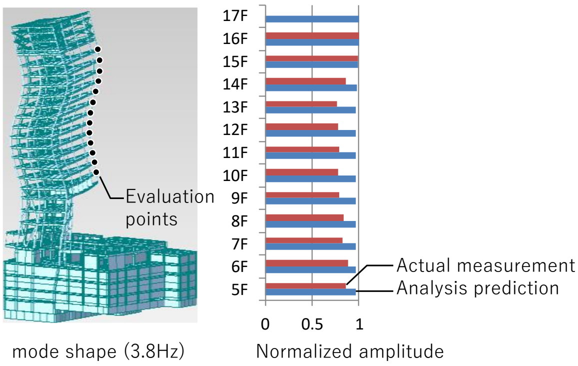

Fig.4 Analysis result (mode shape and standardized amplitude)

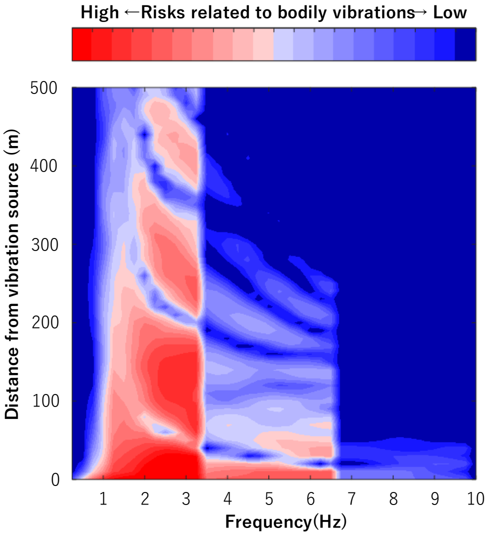

Fig.5 Example of ground vibration analysis

It should be noted that the agreement of the predictive analysis results with the actual measurements, as in this example, is the result of accumulated know-how that cannot be achieved overnight, such as setting the excitation force, setting of modeling methods and damping ratio, and methods of confirming vibration modes without overlooking problems, based on the results of comparing and verifying many actual measurements and predictions.

Herein, we introduced an analysis example of the effect of vibrations on the same building. However, for impacts on surrounding buildings, there are some cases in which the ground vibration generated at the location of the surrounding buildings is obtained by FEM analysis that models the ground, and predictions are made by considering the input loss to the building and resonance amplification within the building.

Fig. 5 shows the relationship between the frequency and the distance from the vibration source as an example of the ground vibration analysis we conducted. The figure visualizes the risk of bodily sensation vibration after inputting the excitation force data described in the previous section into the FEM analysis model and considering resonance amplification. Based on this figure, we developed solutions from the initial stage of the project that share the risks assumed by “human rhythmic action” among the parties involved and utilized them for location and layout considerations, countermeasures planning, and so on.

We also worked daily to improve the analysis accuracy by comparing the results with actual measurements. However, due to various restrictions during concert performances after the completion of construction, it is often difficult to measure vibrations in the surrounding grounds and buildings. In order to improve the accuracy of prediction, we will continue to collect and accumulate data that allows comparison of actual measurements and predictions.

3 Consensus building

3.1 Design target value

The setting of target values and the consensus building of those values among the parties involved in the project are particularly critical in the early stages of design. First, we describe the points to be considered in setting the target values.

Fig. 6 shows the vibration level waveform measured at a certain location during the concert performance. This waveform was measured while playing a song approximately four and a half minutes long, but it can be seen that there is a period in which the vibration level maintains a high value for approximately 30 s in the middle of the song and over 60 s at the end of the song. The duration varies depending on the song being played, but the vibrations generated during concert performances are characterized by a duration longer than those caused by walking.

For over 10 years, we have been conducting research based on sensory tests[6)-9)], focused on the efforts of duration on bodily sensations and evaluations of this “human rhythmic action”. The results of this research were reflected in the Environmental Standards of the Architectural Institute of Japan in the 2018 revision of the “Standard for the evaluation of habitability to building vibration”[10)]. The author was also listed as one of the authors of this Habitability Evaluation Standard.

According to this Habitability Evaluation Standard, vibrations lasting 10 s or more are perceived +5 dB (1.78 times) greater than those lasting 1 s or less, making them easier to perceive. For human rhythmic action, it is necessary to pay close attention to the fact that a target value should be set 5 dB stricter than compared to the target value of walking vibration in offices and commercial facilities even for the same use and an even stricter value for uses that require a more stable environment.

Conventionally, design target values for habitability were set and evaluated based on the maximum value of the amplitude of acceleration, etc., based on academic society guidelines. However, in some cases, this 5 dB difference in sensation due to duration time has been a fatal problem in human rhythmic action. We sincerely hope that the Architectural Institute of Japan Environmental Standards, which considers the duration element, will be widely used.

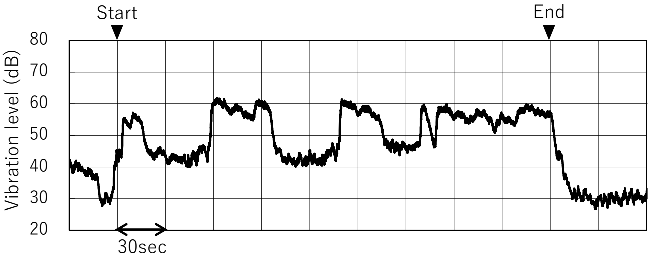

Fig.6 Example of vibration level waveform during concert

Photo 2 Vibration experience system

3.2 Consensus building by bodily sensation

As mentioned in the previous section, human perception of vibration varies greatly depending on not only the magnitude of acceleration but also its frequency and duration. It is not an overstatement to say that it is extremely rare for people to be able to imagine the actual feeling of vibration based only on values of ○ cm/s^2 for the acceleration amplitude and *V*-○ for the habitability evaluation standard[10)].

Therefore, when we deal with a project in which there is concern about vibrations during concert performances, we gather building owners, designers, builders, and other parties involved to ensure that the consensus-building process using the vibration experience system shown in Photo 2 is incorporated.

We believe that this consensus-building method, in which all parties involved share an awareness of issues in the early stage of a project, is considered to be an indispensable process for projects where human rhythmic action is a concern.

4 Countermeasures

4.1 Examples of countermeasures on the vibration source side

As mentioned at the beginning of this report, the vibration generated during a concert has an extensive propagation range, so it is practically impossible to apply countermeasures to the surrounding ground and wide-area buildings, and it is a phenomenon for which countermeasures at the vibration source are desired. In this section, we introduce the latest vibration control system installed in an event hall completed two years ago.

This example is a complex facility with a hotel and a commercial facility adjacent to the event hall. Although the above-ground part is separated by Exp. J, the basement and part of the first floor are integrated into three buildings. The event hall is primarily used for rock concerts and has a capacity of 7,000 people, with a standing floor that can accommodate up to 3,000 people. Since buildings are scattered nearby, it would be challenging to apply countermeasures on the receiving side of each building. Therefore, we decided to conduct three types of countermeasures on the vibration source side. Fig. 7 shows an overview of the vibration countermeasures.

For the first countermeasure, we attempted to reduce the vibration propagation to surrounding buildings using cast-in-place concrete piles with high vertical rigidity and extended the tip of the pile to the support ground with an N value of 60 or more, which has extremely high rigidity. Next, the structural form below the second floor, where the standing floor is located, was made with steel-framed reinforced concrete instead of a steel frame to increase the weight and rigidity and reduce the amplitude of the event hall. Finally, the standing floor is an ultra-low frequency anti-vibration floor with a natural frequency of 1 Hz, which significantly reduces the excitation force applied to the lower structure.

Table 2 shows the specifications of the ultra-low frequency anti-vibration floor, and Fig. 8 shows the planar configuration. The anti-vibration floor has a concrete slab with a thickness of 1,200 mm supported by 44 coil spring units, with damping added by 16 viscous dampers.

The construction of the floor is explained by the mockup of the anti-vibration floor shown in Photo 3. After setting the coil spring in a preloaded state and installing a PC plate (200 mm thick) that also serves as a formwork, concrete with a thickness of 900 mm was poured over two separate sessions. Subsequently, the preload of the spring was released, and a 100-mm thick concrete was placed while adjusting the floor level.

The ultra-low frequency anti-vibration floor suppresses the vibration that occurs on the anti-vibration floor during concert by securing the weight through its concrete, setting a damping of over 10% with the viscous damper, and furthermore setting an eigenfrequency to 1 Hz, which is a frequency region where the excitation force of human motion is small (see Fig. 2). This reduces the "fluffy feeling" felt by spectators on the floor, and reduces the difference in level between the anti-vibration floor

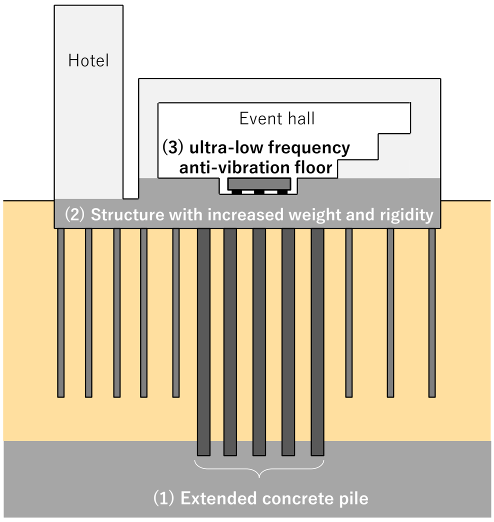

Fig.7 Overview of vibration countermeasures

Table 2 Specifications of anti-vibration floor

Floating floor area	1137.6m^2
Slab thickness	1,200mm
Slab weight	31,834kN
Assumed number of spectators	3,000 people
Spectator weight	1,764kN
Floating bed total weight	33,598kN
Spectator weight / slab weight	6%
Vertical stiffness of a coil spring unit	3.39kN/mm
Number of coil spring units	44 units
Total vertical stiffness	149.16kN/mm
Frequency of Floating floor	1.0Hz

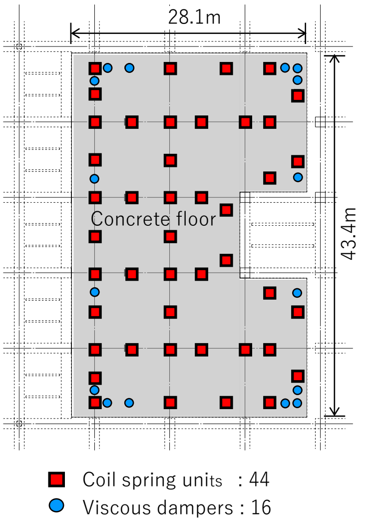

Fig.8 Configuration of anti-vibration floor (plan view)

and the structure, thereby avoiding the risk of spectators tripping.

The vibration reduction effect of the mock-up has been verified in detail in the previous reports 11) to 14), and the vibration in the frequency band above 2 Hz, which was conventionally difficult to counteract, has been successfully reduced to approximately 1/2 to 1/3 of its original level.

The complex is equipped with a total of eight sensors to monitor vibration during concert performances, and it has been confirmed that the set design target values are still being met more than two years after the completion of construction.

4.2 Examples of countermeasures on the receiving side

If the locations where bodily sensation vibration occurs can be limited by prediction or other means, countermeasures on the vibration-receiving side can be an effective measure.

For example, in the building where the prediction example was introduced in Section 2.2, it was known in advance by simulation that only the 3.8 Hz vibration mode shown in Fig. 4 affects the bodily sensation vibration. Therefore, as a countermeasure, we decided to install a hybrid mass damper (HMD) at the antinode of the vibration mode (where the largest countermeasure effect can be expected). Photo 4 shows the appearance of the HMD. For the HMDs, two units with a vibration mass of 500 kg, adjusted to a natural frequency of 3.8 Hz, and vibrated by a servo motor (actuator) with a maximum thrust of 1,100 N, were installed.

Vibration tests using the HMD confirmed that they can generate vibration that can reduce the vibration generated in the high-rise building to 1/3 of its original level, and that the vibration can be suppressed below the design target value of 1.5 cm/s^2 (0-P) or less; after confirming the above, this building was completed.

Other countermeasures on the receiving side include tuned mass damper$^{15)}$, but accurate prediction and consensus building based on the prediction results are indispensable to determine whether to introduce any of these measures.

Photo 3　Mockup of anti-vibration floor

Photo 4　Example of HMD installed in the building on the receiving side

Photo 5　Example of HMD installed in the building on the receiving side

5 Verification

Verification of the level of vibration that occurs when the system is operated by a large number of people in a concert hall is important both in terms of performance verification and in terms of confirming the validity of the predictions and countermeasures. The following are the merits and precautions of verification for each timing of implementation based on our previous experience.

The time of the first verification is when the frame is completed. It is often difficult to collect the number of people who are expected to be involved in the actual operation of the building, and in many cases, the finishing load is not fully applied to the building, so it is possible to confirm whether or not the vibration modes assumed in the prediction analysis will be excited and to what extent the vibration will be generated before the construction is completed. In some cases, it may be possible to determine at this stage whether or not to use damping devices or other countermeasures at this stage.

Photo 5 shows the implementation of the verification (vibration test) conducted by gathering hundreds of workers on the floor of the concert venue. The main advantage of the excitation test, which is conducted when the frame is completed, is that the excitation tempo can be arbitrarily adjusted according to the sound or music played in the venue. Immediately before the excitation test, we used predictive analysis to measure the natural frequency of the location where shaking is a concern. Then, we planned a excitation menu at a tempo that resonated with that frequency. This is based on the fact that it is not possible to capture resonance phenomena only with vibrations at fine frequency increments, such as 2.0 Hz, 2.5 Hz, and 3.0 Hz, and risks may be overlooked.

The next time of verification is at the time of completion of construction. At this point, it is challenging to change the countermeasure policy depending on the verification result; hence, the main purpose is to confirm whether the target values have been met. In many cases, the verification is not conducted immediately before the completion of construction because it is judged that an actual concert after the completion of construction is more suitable as a performance verification than a simulated excitation by workers.

The last time for verification is when concerts are held after construction is completed. However, since the vibration generated differs depending on the artist and song, simply confirming that the target value was satisfied with a single measurement does not ensure safety, and there are cases where the verification takes a long time (months or years). It is also necessary to plan for the verification budget from the design stage.

The above is one example of verification work for a wide variety of human rhythmic actions, and the accumulation of know-how and constant efforts through numerous examples are required to eliminate any “overlooked aspects” or “omissions” and to prevent any such problem that may occur.

6 Conclusion

The measures to deal with vibration caused by human movement during concert performances are classified into four steps: prediction, consensus building, countermeasures, and verification, and the issues, key points, and case studies for each step are described.

Plans to build and rebuild stadiums and arenas are currently being promoted as a national policy, and facility development is expected to continue throughout the country even after the Olympics and Paralympics. Since stadiums and arenas play a central role in regional revitalization and are used for various purposes, such as concerts, in addition to sports, it is expected that the need to deal with human rhythmic action will increase in the future. We hope that this study will serve as a reference for the planning and design of these projects and that it will be helpful to the development of society.

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