

## Development of the sound-and-vibration-proofing method (suspended seismic isolation method) for buildings under elevated railway tracks



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JR East and Takenaka Corporation have jointly developed the "suspended seismic isolation method" which allows realization of a high quality living environment under elevated railway tracks, where noise and vibrations generated by trains have been a large issue. In this suspended seismic isolation method, a frame of steel supporting posts and beams is created at the posts of a viaduct, and from that frame, a structure is suspended by suspension materials equipped with rubber cushions at the top and bottom. The suspended building slowly swings to the sides when an earthquake occurs or when a strong wind blows so that it can largely reduce the horizontal force that would affect the building or the viaduct. We conducted an experiment with an actual size test model followed by detailed analyses, and confirmed its sound-and-vibration-proofing effects and also that this structure would have only a small impact on viaducts at the time of an earthquake. As for indoor vibrations caused by trains, the suspended structure successfully reached the desirable level (V-0.75) for a bedroom (residence) at the time of a train passing according to the residence performance evaluation by the Architectural Institute of Japan. At the same time, as for its noise level, it has realized the desirable environment of a third-class hotel & residence level according to the standards on sound insulation by the Architectural Institute of Japan. At this time, there is a plan to construct a hotel using this method at Maihama station of the Keiyo line.

● **Keyword** : noise, vibration, structure-borne sound, viaduct, suspended seismic isolation, and rubber cushion

### 1 Introduction

Although space under elevated railway tracks has been used as restaurants or warehouses, further business development such as the use of this space as sports gyms or "super sento (amusement establishment with a variety of public baths)" has been planned. However, it has been difficult to use this space for hotels due to the poor quality vibration and noise environment of the surroundings even though such unused space is valuable in cities.

It was therefore necessary to develop a new engineering method to solve these vibration and noise issues under elevated railway tracks so that the JR East Group would be able to advance with its business development plans. Among the potential locations where this method could be applied, Maihama station had an increased demand for development since it is a gateway to the Tokyo Disney Resort and also increased demand for hotels was expected due to the opening of Tokyo Disney Sea in September 2001.

### 2 Technical development

#### 2.1 History of development of the suspended seismic isolation method

As an engineering method to solve the vibration and noise issue under elevated railway tracks, the suspended seismic isolation method was developed.

##### 2.1.1 Prior technology

In buildings near railroads, noise that is transmitted through the air

(air-borne sound), vibrations that are transmitted through building frames, and noises generated by these vibrations shaking the walls or finishing materials of ceilings like speaker cones (structure-borne sound) become problems. As a solution to these problems, a paddleboard, double wall, and double ceiling may be installed, as seen in Figure 1. This method, however, incurs high costs, and the space will become smaller. The effectiveness of this solution is that it can ensure a sound environment with a noise level of 50 dB (A), which is the level of noises in offices in general. In space where silence is required such as in a hotel room, it is necessary to limit the noise level to about 40 dB (A); therefore, the effectiveness of this solution is not sufficient. Hence, a new technology was developed in order to realize quieter space.

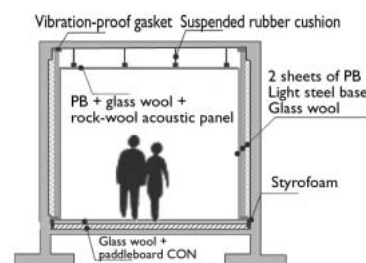


Fig.1: The conventional sound-and-vibration-proofing method

##### 2.1.2 Issues

In general, train vibrations come in from the foundation of a building. The vibrations are not damped inside the building, and generate sensory vibrations, structure-borne sounds, and air-borne sounds there. Although air-borne sounds can be controlled with exterior walls,

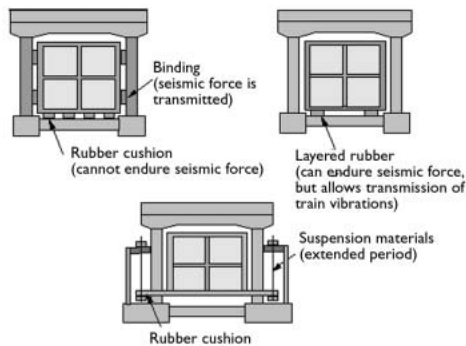


Fig.2: Examples of reviewed systems

interior materials, and sound-proof sashes, it is not easy to control the vibrations that are transmitted through the frames of the building.

The ideal vibration-proof measure would be to completely separate building frames from the frames of a viaduct, resulting in an image where a building floats under an elevated railway track. Constructing a building on layered rubber, which is used in earthquake-absorbing buildings, may be a realistic idea, but such rubber is designed to handle horizontal movement of earthquakes and has high rigidity in the vertical direction, resulting in transmission of vertical vibrations. And so, the idea of "suspending a building, and installing rubber cushions on the top and bottom of the suspension materials" was born so that seismic force can be reduced and vertical vibrations will not be transmitted. This idea also has the advantage of making implementation of the measure easy since vibration transmission is considered to enter the building from specific "points" such as suspension materials instead of a broader "area" such as the building foundation or the floor. Therefore "vibration-proof measures" and the "bearing force of a viaduct" were the most important technical development issues.

## 2.2 The mechanism of suspended seismic isolation

### 2.2.1 System structure

Figure 3 shows the system structure of the suspended seismic isolation method. In this system structure, an upside-down L-shaped supporting base is fixed to individual pillars of a viaduct, and from the base, a building is suspended by suspension materials equipped with rubber cushions on the top and bottom. This system allows the building to be vibration-proof when a train passes, an earthquake occurs, or a strong wind blows. Also, in order to ensure indoor habitability, dampers are installed under the floor so that daily horizontal motions are prevented. Rubber is used with the damper mechanism as a vibration-proof measure.

### 2.2.2 Earthquake-proof mechanism

In the suspended seismic isolation method, a building is suspended

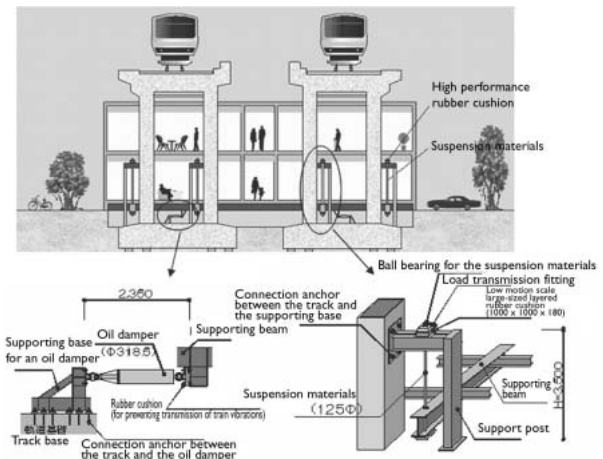


Fig.3: System structure

from a viaduct as seen in Figure 4 (a). Therefore, the building slowly moves in the horizontal direction when an earthquake occurs or when a strong wind blows. By swinging the building over a longer time cycle, it is possible for the building to escape from the earthquake motions having powerful short-term components. This allows a large reduction of external force that interacts with the building, and also the force applied to the viaduct will become smaller than the prior engineering method in which a building is installed directly onto the foundation of the viaduct as seen in Figure 4 (b). Thus, it has become possible to make buildings safe structures by fending off the powerful earthquake energy and to maintain structural safety of viaducts at the same time. It should also be noted that sufficient space has been provided around buildings to secure safety so that buildings will not be damaged by crashing into viaducts in case of huge earthquakes or strong winds.

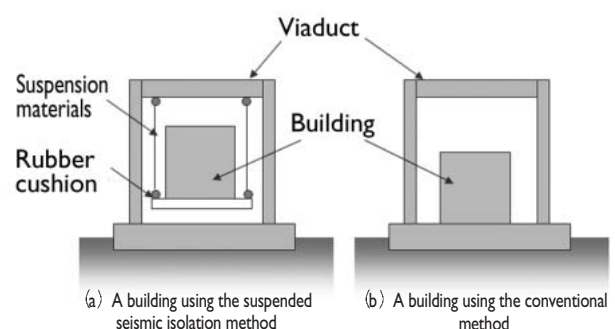


Fig.4: A building using the suspended seismic isolation method and a building using the conventional method

### 2.2.3 Sound-and-vibration-proofing mechanism

Figure 5 shows the suspension frame unit in detail. This unit attenuates vibrations transmitted from pillars or support pillars of a viaduct by transmitting vibrations to the top rubber cushion -> suspension materials -> bottom rubber cushion -> support beam -> floor slab, resulting in control of vibrations and structure-borne

sounds. Note also that the roof, walls, and floors of the building are made of reinforced concrete so that these components can work with interior materials to control air-borne sounds.

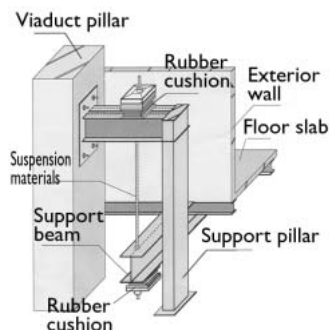


Fig.5: Detailed view of the suspension frame unit

### 2.3 Examination with an actual size test model

For the suspension frame unit, its safety and sound-and-vibration-proofing performance in case of earthquake or strong wind were checked by using an actual size test model. Table 1, Figures 6 and 7 show an overview of the test model. The interior design of the test model simulated a guest room of a hotel, and thus had a bed and an air-conditioner. The test model underwent a number of improvements as the problem of resonance, which was generated in the suspension frame unit or the interior materials due to train vibrations, was solved. As a result, the suspension frame unit reached its specified target performance level.

Figure 8 shows the level of indoor noise of the actual-size test model measured when a train passed, and Figure 9 shows floor vibration under the same conditions. The test results show that the suspended seismic isolation method can dramatically reduce vibrations and noises. The indoor noise level is at the level of the desirable environment of a third-class hotel & residence according to the "standards on sound insulation for buildings" by the Architectural Institute of Japan as shown in Table 2. The indoor vibration level is at a desirable level (V-0.75) for a bedroom (residence) according to the "residence performance evaluation related to vibrations of buildings" by the Architectural Institute of Japan as shown in Table 3.

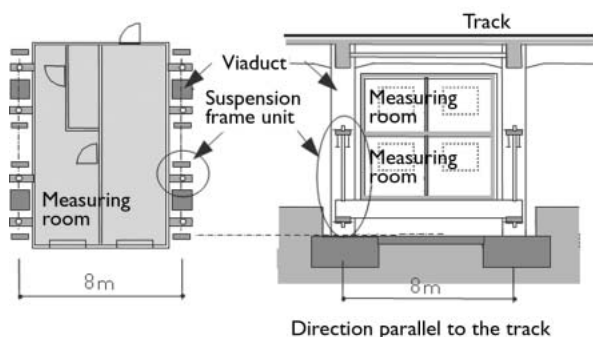


Fig.6: Floor plan and cross-section of the actual size test model



Fig.7: Inside the actual size test model

Table 1: Overview of the test model

Rigid steel-framed two-story structure
Floor and walls made of reinforced concrete
Gross weight: 220 tons
Suspension materials: L = 3.4 m
Designed primary natural period: 3.7 seconds

Table 2: Noise classification

Classification		Super-high class (special specifications defined by the Conference)	First class (recommended level defined by the Conference)	Second class (standard level defined by the Conference)	Third class (accepted level by defined by the Conference)
Sound isolation level	Average difference of sound pressure between rooms	-	D-55	D-50	D-45
	Level of impact noises on the floor	-	D-40	D-35	D-30
Difference of sound pressure between inside and outside	Impact noise by light objects	L-40	L-45	L-50	L-55
	Impact noise by heavy objects	L-45	L-50	L-55	L-60
	50 dBA	D30-II	D-25	D-20	D-15
	60 dBA	D-35	D-30-I	D30-II	D-25
Indoor noise level	70 dBA	D-40	D-35	D-30-I	D30-II
	80 dBA	-	D-40	D-35	D-30-I
		-	N-35	N-40	N-45
		-	N-35dB(A)	40dB(A)	45dB(A)

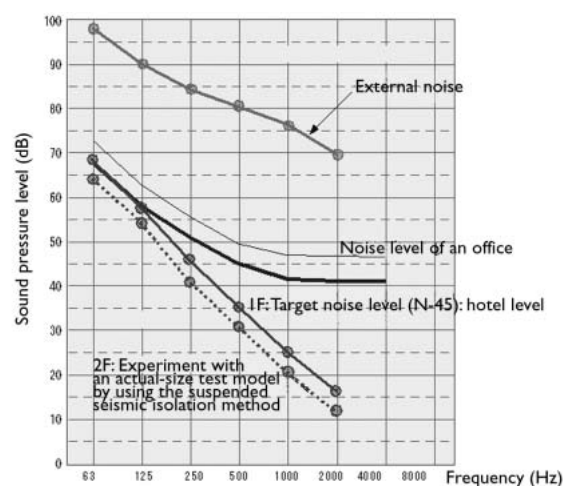


Fig.8: Indoor noise

Table 3: Vibration ratings

Vibration type		Type 1			Type 2	Type 3	
Building and application	Rank	Rank 1	Rank 2	Rank 3	Rank 3	Rank 3	
	Residence	Living room and bedroom	V- 0.75	V- 1.5	V- 3	V- 5	V- 10
Office		Meeting room and reception room	V- 1.5	V- 3	V- 5	V- 10	V- 30
		Typical office room	V- 3	V- 5	About V-5	About V-10	About V-30

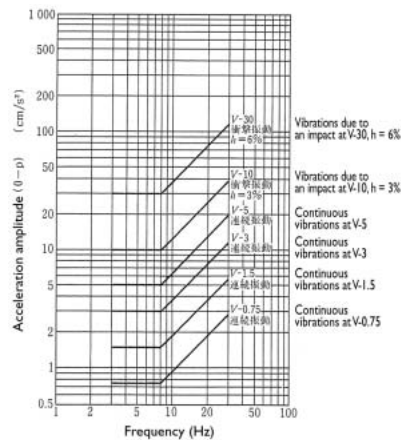


Fig.9: Indoor floor vibrations

## 2.4 Technical committee

This is a special engineering method in which a structure is suspended from a viaduct, and it is a civil engineering structure; therefore, an independent structural safety examination based on various technical standards for both the suspending and suspended materials. At the same time, it was necessary to solve various problems regarding design and construction for this technology that covered integration of the fields of viaducts and buildings. For this reason, the "Technical Committee of Building Design Method under Elevated Railway Tracks (chairman: Tsutomu Kato, Professor Emeritus of the University of Tokyo)" was held and academic experts of architecture and civil engineering famous in the fields of earthquake-proofing and basic structures participated. The committee then conducted technical reviews to solve the various problems.

## 3 Overview of the hotel

As seen in Figure 12, the hotel was constructed under the elevated railway track of the east side, or Soga side, of Maihama station in Urayasu-city, Chiba. This space was originally unused land. The hotel was a two-story structure with reinforced concrete walls, and its total floor area was approximately 6,000m<sup>2</sup>. The wing with guest rooms, to which the suspended seismic isolation method was applied, had a gross weight of 4,500 tons and was suspended by 44 steel rods. The guest room wing as shown in Figures 10 and 11 had approximately 80 rooms, and the area of each room was relatively spacious and was 36 m<sup>2</sup>. Each room was also equipped with a washroom with a shower area and a toilet stall. Each room could hold two to four guests, allowing flexible operation. The wing is also equipped with shops and a parking lot.

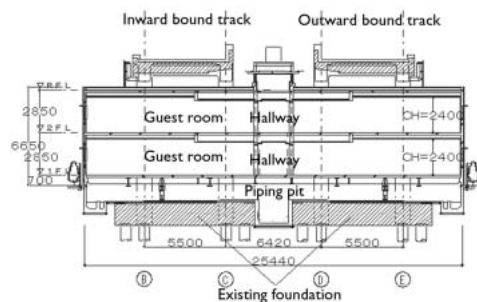


Fig.10: Cross-sectional view of the hotel

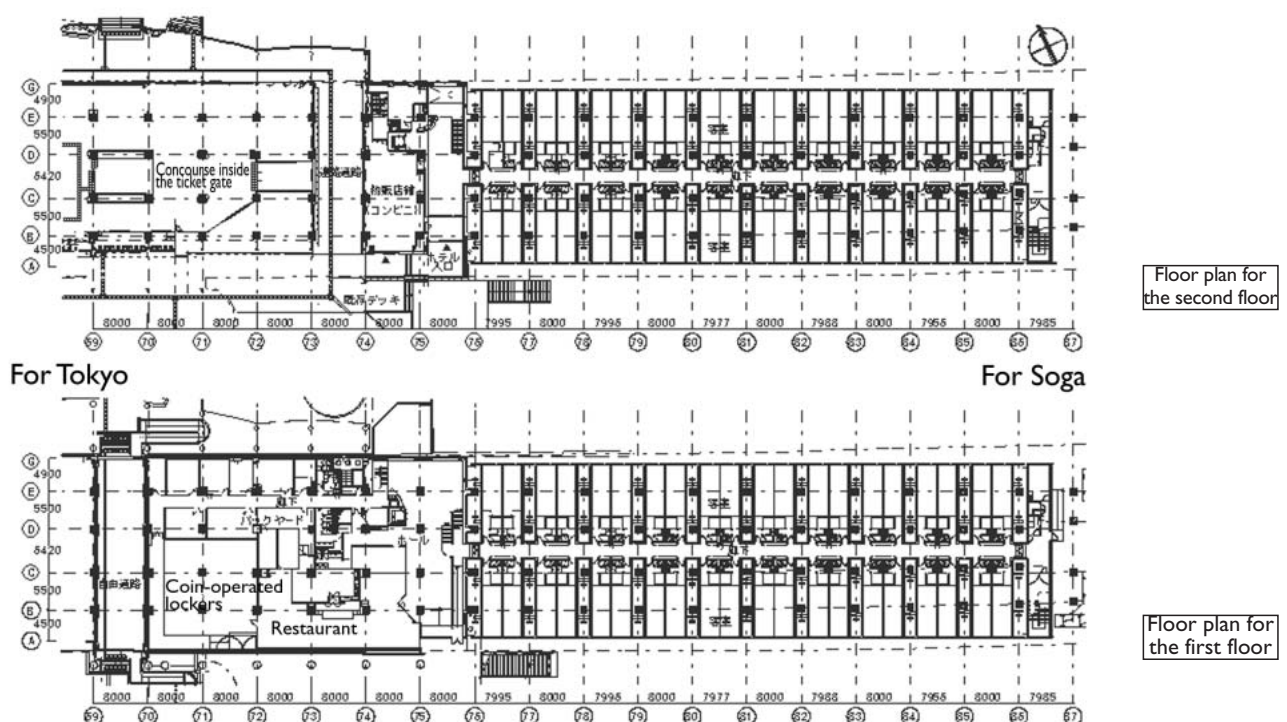


Fig.12: Floor plan





Fig.11: Exterior view of the building and perspective drawing of a guest room

## 4 Design and construction

### 4.1 Design

#### 4.1.1 Structural design

The viaduct used this time had been designed to handle the loads of medium layer slabs for future expansion. Since these medium layer slabs had not yet been constructed, it was necessary to compare and examine the cross-section power of the viaduct with the loads of medium layer slabs in normal times and in case of earthquakes, and the cross-section power of the viaduct when additional external force was applied from a suspended structure. As a result, the additional external force of the building that would interact with the viaduct was below the maximum load for the future expansion; therefore, it was confirmed that the viaduct met the civil design standards of the time of its construction.

For the building, time-history response analyses were conducted for simulated earthquake motions or typical seismic waves that were expected at the construction site. As a result, relative story displacement of the building was very small and below 0.1 cm (below 1/2850) both for "earthquake motions that occur in rare cases (level 1)" and "earthquake motions that occur in extremely rare cases (level 2)." Stress intensity of the building was also below allowable maximum stress intensity; therefore, it sufficiently met the target earthquake-proof performance standards. These findings confirmed

that no parts of the building would be damaged or destroyed due to seismic loads. For the frame that supported suspension materials, its stress intensity was below its allowable maximum stress intensity. Horizontal deformation of the entire suspended building was below 30 cm for "earthquake motions that occur in extremely rare cases (level 2)" thus clearing the design criteria, and it was confirmed that the building would not collide with the column base of the viaduct. Note that, the oil dampers used this time are not the conventional uni-flow type. The bi-flow type, which is small, light, with a maximum speed of 100 cm/sec, and rigid on the compressed side, was partly upgraded and used.

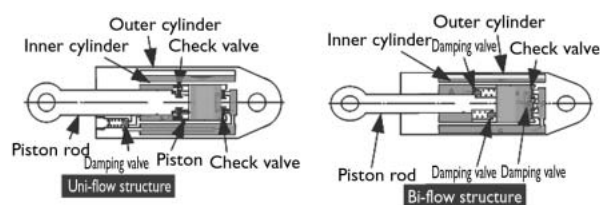


Fig.13: Oil damper

#### 4.1.2 Sound-and-vibration-proofing design

Changes were made to the specifications in response to the result of experiments using the test model and the analyses:

- 1/ Point of suspension: 2 points per viaduct -> 1 point
- 2/ Support beam of the building: Steel frame, partially made of reinforced concrete -> Reinforced concrete (entirely)
- 3/ Building: Steel frame and reinforced concrete floor and walls -> Wall-type reinforced concrete

With these changes, load distribution became leveled, natural vibration frequency of the rubber cushion was reduced, and vibration-proof performance improved due to the increased damping at the support beam and also due to improved building rigidity. The material for the rubber cushion shown in Figure 14 was crude rubber of a low motion scale type to minimize the difference between the designed natural vibration frequency of 3 Hz and actual vibration frequency. Also, this rubber cushion was not layered rubber, but it still would deform in the horizontal or vertical direction should an earthquake occur. Therefore, we conducted a loading test with the rubber cushion in the horizontal and vertical directions to ensure the safety in case of earthquake.

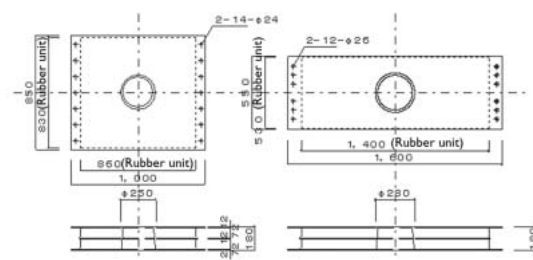


Fig.14: Rubber cushion viewed from above

## 4.2 Administrative procedure

### 4.2.1 Structural performance evaluation

Following the instructions of the Land, Infrastructure and Transportation Ministry, this building was evaluated for its structural performance based on the Building Standard Law and was approved by the Minister of the Land, Infrastructure and Transportation. Specifically, this building was examined by the Building Center of Japan, a third-party organization. Rubber cushions and dampers that were not specified materials according to Article 37 of the Building Standard Law were used in parts where loads would be supported, and the strength of these parts were also examined during the course of the performance evaluation. Note that the structural safety of the viaduct had already been confirmed by JR East, a certified railway operator.

### 4.2.2 Evaluation of fire resistance

The building was a complex facility constructed as an addition to the existing station building. Since the lot was not specified as a primary or secondary fire zone and also the station building was not categorized as a special building in accordance with Article 27 of the Building Standard Law, it did not legally have to be constructed as a fire-proof building. However, since the existing station building was a fire-proof establishment and an application had to be made for the station building and the hotel as an integrated establishment, according to the municipal bylaw of Chiba prefecture, the hotel was applied for as a fire-proof establishment.

Since the suspension materials and rubber cushions used in the suspended seismic isolation method were categorized as major components of the building, they needed to be fire-proof. There are however no fire-proof certificates applied to rubber cushions, so we conducted a fire-proof performance examination based on Article 108(3) Section 1(2) (route C) of the Building Standard Law enforcement regulation in order to obtain a certificate from the Minister of the Land, Infrastructure and Transportation.

Conventionally, examination of fire-proof performance could only be conducted through design specifications. However, since the revision of the Building Standard Law of 2000, examination through performance design has been accepted. According to the current law, "route A" refers to the conventional examination method by using specification design, "route B" refers to the examination method covered in announcements, and "route C" refers to the examination procedure in which an advanced examination method is used, a specified performance evaluation institute evaluates the results, and the Minister of the Land, Infrastructure and Transportation approves the results. In the case of this hotel, although the entire establishment

should have been examined by using one fire-proof performance evaluation method, the part of the building with guest rooms and the other parts were considered as different establishments due to their structure and fire-proof standards. Therefore, route C was applied to examine the fire-proof performance of the guest rooms and route A was applied to examine the fire-proof performance of the other parts of the establishment.

## 4.3 Construction

### 4.3.1 Erection of steel framing

Selection of heavy equipment to be used in construction with low headroom under an elevated railway track is limited, and it thus greatly affects the construction process. In this case, too, since the land area was small, construction methods such as a grounding or erection of steel framing had to be reviewed and discussed. Figure 15 shows a picture taken at the time of erection of the steel framing. For the erection work, 4.9 ton mini crawler cranes, 3 ton forklifts, and 1 ton trucks were used. Especially, girders that were extremely heavy were suspended by two 4.9 ton mini crawler cranes.

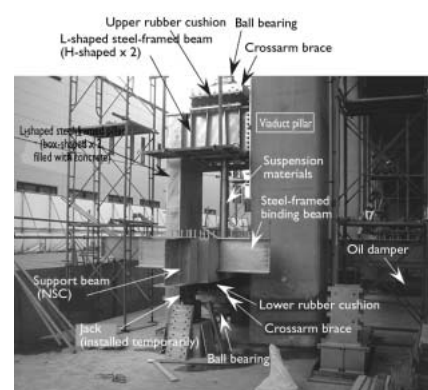


Fig.15: Erection of steel framing for the suspension frame unit

### 4.3.2 Jack up/down work

Figure 16 shows construction procedures of the suspended seismic isolation method. Jack up work refers to a procedure in which the load supporting unit of the first floor frame is moved to the permanently installed rubber cushion and suspension materials from the temporarily installed jack under the floor. Floor steel framing for the first floor was erected, and concrete was cast in the outer circumference of the first floor while this temporary jack supported the load supporting unit. For this process, hydraulic jacks installed at the top of the suspending steel rods were used.

Step 1: Compressive deformation occurs to the rubber cushion until the building is lifted from the ground.

Step 2: The building is raised by the hydraulic jack.

In order to raise 44 suspending points with jacks all at the same time,

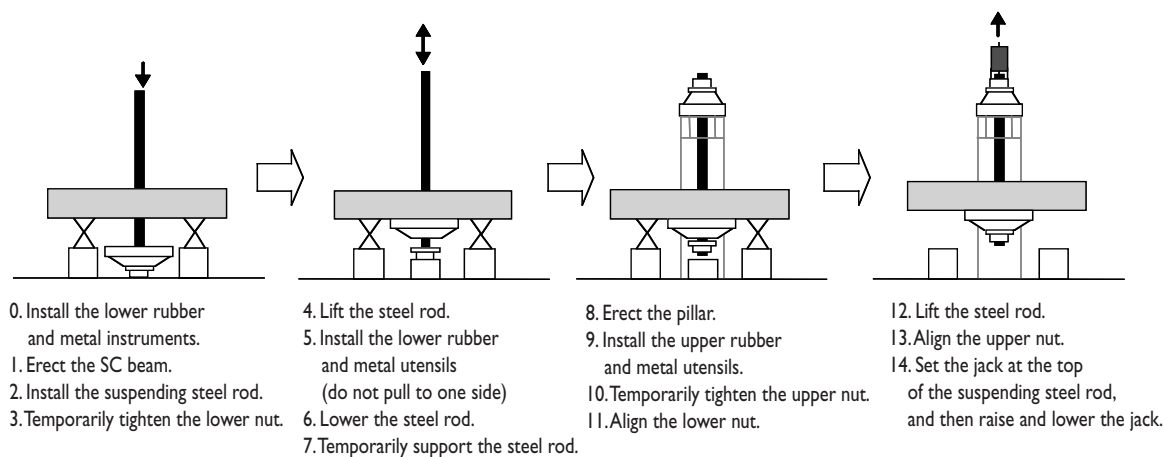


Fig.16: Construction procedures when using the suspended seismic isolation method

the work process was centrally controlled by computer. In Step 1, the process was controlled based on loads imposed on the rubber cushion, and in Step 2, the process was controlled based on the magnitude of displacement by the lift.

After the suspending points were raised to the specified height, upper nuts were tightened and the jacks were released. Loads were then imposed on the suspending steel rods (jack down). Through the series of the jack up/down work, loads were imposed on individual viaduct pillars for the first time. The magnitude of displacement by jack lift was estimated from: level before jack up, downward displacement at the time of shifting the loads to the suspending rods: loads due to casting of concrete on the second floor or due to finishing work; and amount of creep of the rubber cushion.

## 5 Design and construction

Hotel Dream Gate Maihama is the first project to use the suspended seismic isolation method. A patent is currently pending for this engineering method, and this method has also been selected as a project that is promoting the spread of new mechanical system\*1# by MSSF.

When using the suspended seismic isolation method, it is necessary to take certain conditions into consideration such as endurance of a viaduct or headroom. Also, in terms of business profitability, the land must meet geographical conditions that are suitable for the market, and it is thus not possible to construct a hotel under every elevated railway track. Still, the development of this new technology has allowed construction of an accommodation facility, whose development had been restricted by noises and vibrations under elevated railway tracks, and this technology is expected to enhance the potential of future development.

\*1: A subsidized project for practically applying the new technology or system. Promotion of wide use of the technology or system must be determined necessary, and also, research and development of the technology or system must be at the specified level.