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Study on soft-landing mechanism in base-isolation device

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ABSTRACT: A study on a "Soft-Landing Mechanism" was carried out in an effort to develop a base-isolation method designated to reduce the seismic forces acting on nuclear fuel facilities and to secure the safety of such facilities even in case of excessively strong ground motion. The soft-landing mechanism is designated for rubber bearing base-isolation system. The soft-landing base has a sliding surface on which the superstructure is set to land softly by using the subsidence of rubber bearing accompanying lateral deformation in an earthquake. The efficiency of the soft-landing mechanism was confirmed by tests and analyses and it was found that the system developed here would be applicable as a safety device for base isolated buildings.

1 INTRODUCTION

In Japan, earthquakes are so frequent that nuclear power facilities must satisfy extremely strict earthquake resistance standards.

Depending on the requirements for the earthquake resistance, design seismic forces considered in nuclear fuel facility are between 1.5 and 3 times greater than those for ordinary buildings. Such buildings are designed to fully guarantee the safety of the equipment installed inside, and consequently, the buildinds are extrmely sturdy and relatively expensive to construct.

By adopting a base isolation system, it is possible to improve the earthquake safety margin for large scale nuclear fuel facilities, and to rationalize the design process.

To realize such a system however, it is necessary to (1) determine the appropriate design input seismic waves for base-isolated structures, (2) establish an accurate dynamic analysis method, and (3) develop a highly reliable base isolation system.

This paper reports on the development of a soft-landing mechanism briefly called Soft Landing. The paper includes the results of characteristics tests and shaking table tests conducted on reduced models in order to confirm the feasibility of the system when applied to a base-isolated structure as well as dynamic limit tests using a practical model and a study on the application of the system in a large nuclear fuel facility building. All test have been performed in order to guarantee the reliability of the base isolation system.

2 DEVELOPMENT OF SOFT LANDING

One method of developing a reliable base isolation system is the incorporation of Soft Landing in a previously developed base isolation system. The latter, for instance, may be composed of laminated rubber bearings made of natural rubber and steel bar dampers (hereafter called rubber bearings and dampers).

Soft Landing would use the subsidence which accompanies the horizontal deformation of rubber bearings to gently lower the superstructure onto a platform equipped with a sliding surface. This would prevent the excessive deformation of the base isolation device, as well as any damage to the base isolation system, the superstructure, connecting pipes etc. At the same time, it will reduce the acceleration transmitted to the superstructure to the lowest possible level, even when the input seismic waves exceed the design seismic waves.

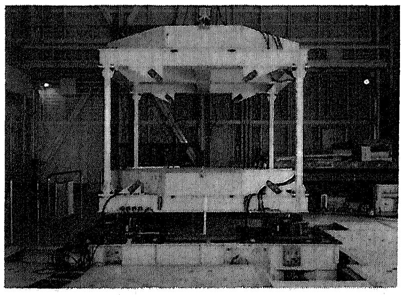


Photo.1 Reduced Base-isolated Model

2.1 Characteristics tests and shaking table tests of reduced base-isolated model

Photo.1 shows the reduced base-isolated model. The superstructure of the reduced model is a single-story steel-frame , having a total weight of 8 tons, distributed equally between the first floor and the roof. The primary natural period of the superstructure is 0.3 second. The base isolation device is composed of 2-ton natural rubber bearings, cantilever beam type PC steel bar dampers, and Soft Landings. Fig.1 shows the base isolation elements consisting of rubber bearing, damper, and Soft Landing, while Fig.2 shows the outline of the base isolation system. At the sliding plate of Soft Landing, Ethylenetetrafluoride resin is used to obtain favorable damping capacity and soft landing effect.

1) Static tests on reduced model

Static tests were performed to investigate the basic characteristics of each of the elements composing the base isolation system.

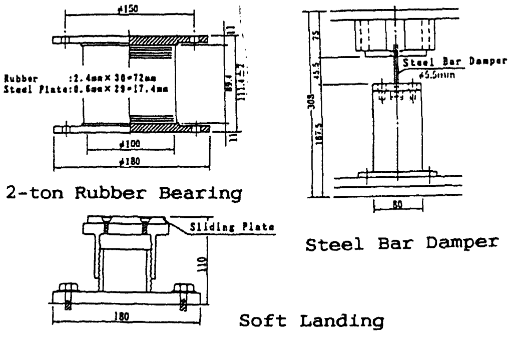
The horizontal restoring force characteristics of the base isolation system composed of rubber bearings, dampers, and Soft Landings at axial force of 2tons are summarized in Fig.3. Fig.4 and 5 show the vertical displacement and the bearing load of Soft Landing. In this case, stable restoring force characteristics are indicated up to horizontal displacement of ±10 cm which is equal to the diameter of rubber bearing, and there is no risk of buckling of rubber bearings.

The Soft Landing mechanism is as follows. Due to vertical displacement of the rubber bearing as horizontal deformation increases, the superstructure lands on Soft Landing and begins to slide. As the weight of the superstructure gradually shifts onto Soft Landing, the frictional resistance (damping) qradually increases. Soft Landing indicates favorable response displacement control function without applying excessive acceleration to the superstructure due to smooth transfer of load and friction, and it prevents buckling caused by the excessive deformation of rubber bearing. The superstructure is restored to its original position by the restoring force of the rubber bearing, even after excessive deformation.

A damper is shown to posses stable spindle-shaped restoring force characteristics up to a horizontal deformation of ± 4cm.

The damping factor of rubber bearing is nearly 3 %, while for a combination of rubber bearing and damper it is approximately 15 %, and that of rubber bearing and damper is approximately 5%.

The analytical values shown with broken lines in Fig.3, 4 and 5 agree well with the experimental results.



2-ton Rubber Bearing

Steel Bar Damper

Soft Landing

Fig.1 Base Isolation Elements

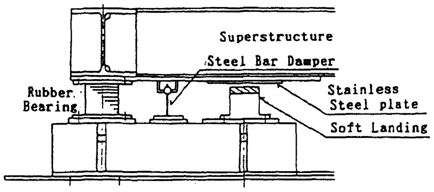


Fig.2 Outline of Base Isolation System.

2) Shaking table tests on reduced model

To determine the earthquake response characteristics of a base isolation structure incorporating a Soft Landing, a test using

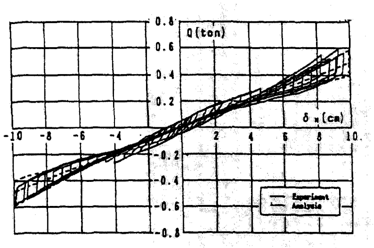


Fig.3 Hysteresis loop.

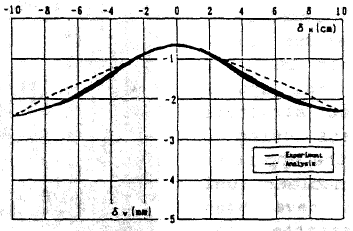


Fig.4 Vertical displacement

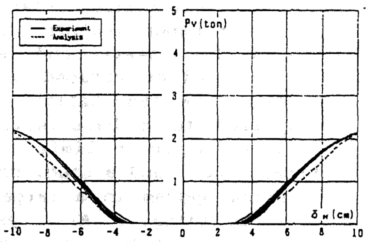


Fig.5 Landing Load.

(2-ton Rubber Bearing, Damper and Soft Landing)

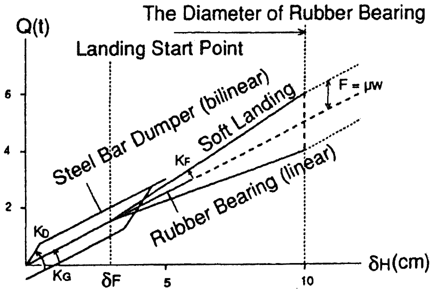


Fig.6 Hysteresis loop (Analytical Model)
(2-ton Rubber Bearing and Soft Landing)

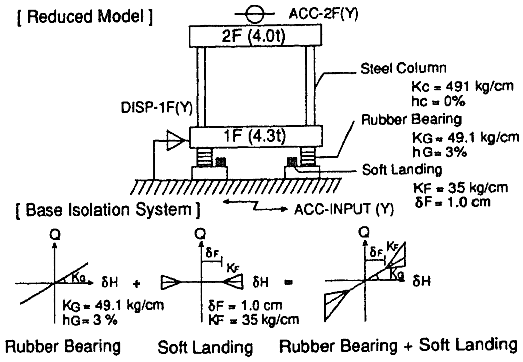


Fig.7 Analytical Model of Reduced Model

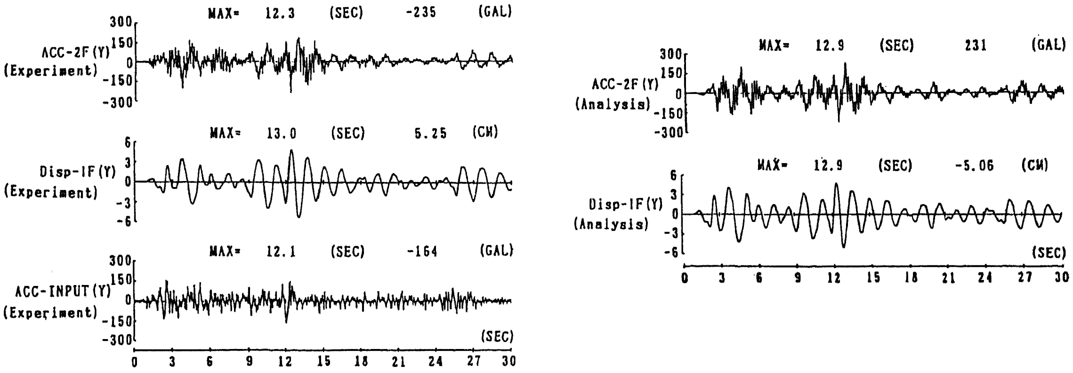


Fig.8 Comparison of waveforms of Reduced Base-isolated Model
[2-ton Rubber Bearing and Soft Landing
EL CENTRO 1940 Wave 160 Gal Input]

the reduced base-isolated model placed on a shaking table (photo.1) was performed, and a simulation analysis was conducted.

Table 1 shows the characteristic frequencies of a steel frame structure with and without base isolation obtained by means of resonance detection and analysis based on a sinusoidal wave excitation test.

Fig.6 shows the analytical model for the restoring characteristics of the base isolation system composed of rubber bearing, damper and the Soft Landing. Fig.7 shows the analytical model of the reduced model. The rubber bearing 'was conceived as a linear spring model, the damper — as a bilinear model, and Soft Landining — as a model with friction of constant gradient (K_F) effective upon initial horizontal displacement (δ_F). Multiple Shear Spring model (MSS model) was used for two directional input.

The present paper reports on experimental and analytical results obtained from tests conducted on a base isolation device combining rubber bearings and Soft Landings without dampers. Fig.8 shows waveforms for acceleration and displacement in the EW direction, when EL CENTRO 1940 waves (EW164gal, NS280gal, UD300gal) were input to the model. The measured horizontal displacement of the rubber bearings was shown to be 5.25cm, and the analytical results almost completely simulate the experimental results. The analysis performed when the same waves were input to the base-isolated model with only rubber bearings revealed that the horizontal deformation of the rubber bearing increases more than 8.45cm, as buckling of rubber bearings may occur. This confirmed the effectiveness of the Soft Landings as a device designed to protect the structure from excessive input, and proved that the earthquake response analysis method was appropriate for use on base-isolated structures with Soft Landings.

Table 1. Eigenvalues of Reduced Models

Test Specimen	Vibration Mode	Experiment	Analysis
Fixed-based Model	1st.	3.67Hz h=0.1%	3.66Hz
Base-isolated Model (Rubber Bearing)	1st.	0.88Hz h=2.5%	0.88Hz
	2nd.	5.12Hz	5.16Hz
Base-isolated Model (Rubber Bearing + Steel Bar Damper)	1st.	1.31Hz h=1.7%	1.31Hz
	2nd.	5.20Hz	5.26Hz

2.2 Dynamic tests on a pratical model

Soft Landing was built with 40-ton rubber bearings. Dynamic limit tests confirmed the performance of Soft Landing as a safety device designed to protect the base isolation system from large deformation caused by an excessive seismic input.

Fig.9 shows the 40-ton natural rubber bearing. The rubber bearing is almost of the same shape as those used in base-isolated buildings. With a total load of 40 tons, its horizontal vibration frequency is approximately 0.5Hz, its vertical vibration frequency is 15Hz, and its allowable deformation is 15cm. Fig.10 shows the Soft Landing. A load cell used to measure bearing load is installed inside the Soft Landing, and its landing surface provides suitable damping force and soft-landing effects through the use of a supermacromolecular polyethylene.

Next we will describe the results of limit tests performed with the dynamic loading test system shown in Fig.11, which provided forced deformation with sine wave horizontal displacement varying in the range from 0 to 35cm at vibration frequency 0.5Hz.

Fig.12, 13 and 14, show the restoring force characteristics, vertical displacement and bearing load of Soft Landing in limit tests conducted on a combination of rubber bearings and Soft Landings. Fig.12 shows that restoring force characteristics are stable up to a horizontal displacement of 35cm (274% of the shearing strain of the rubber bearing), which is equal to the diameter of the rubber bearings, and it also indicates that the rubber bearings are protected from risks of hardening and buckling.

The friction coefficient μ of the Soft Landing is approximately 0.16, and no problems of durability on the sliding surface occurred. From Fig.14, it can be seen that the load acting on the rubber bearing is transferred smoothly to Soft Landing as the horizontal displacement increases.

The value of the damping factor becomes larger as horizontal displacement increases, and attains a maximum of approximately 8%.

The analytical values shown with broken lines in Fig.12, 13 and 14 agree well with the experimental results.

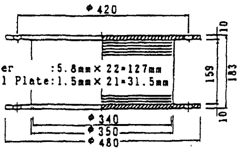


Fig.9
40-ton Rubber Bearing

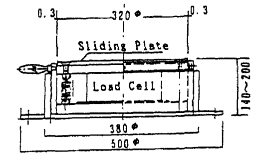


Fig.10
40-ton Soft Landing

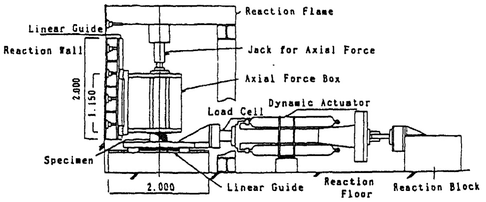


Fig.11 Dynamic Loading Test System

It may be considered from the limit tests that design of a more compact base isolation device with incorporation of Soft Landing is possible since the axial load of the rubber bearing is alleviated and stress is reduced by Soft Landing functioning as a safety device against excessively large input.

The above study demonstrates that Soft Landing is a safety device that will protect base isolation device from excessive input.

2.3 Application to a large scale nuclear fuel facility building

As a preliminary study of the application of Soft Landing in an actual building , we performed an earthquake response analysis on a model equipped with a base isolation device consisting of rubber bearings and dampers, and Soft Landings. The model is designed for use in a large scale nuclear fuel facility building and the actual implementation of the system was investigated.
An analytical model is supposed to be located in Tokai-mura.

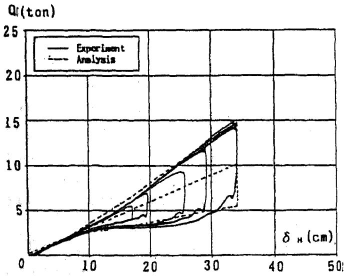


Fig.12 Hysteresis loop

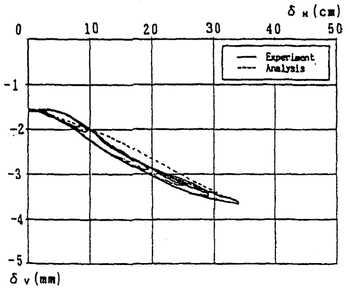


Fig.13 Vertical displacement

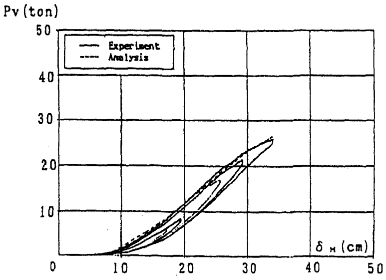


Fig.14 Landing load

(Limit Tests : 40-ton Rubber Bearing and Soft Landing)

1) Actual analytical model

Fig.15 shows the actual analytical model.

The superstructure has a 7-stories with floor plan of 63.9m× 49.1m. Each floor is supported by 4 concentrated columns. The superstructure is considered elastic with a weight of approximately 120,000 tons and damping factor— 3%.

The base isolation device includes 60 rubber bearings with natural period of 3 seconds (design horizontal displacement:40cm, diameter:160cm, surface pressure:100kg/cm^2, damping factor of the rubber bearings:2%).

The yield strength of total dampers is taken to be $Q_Y=0.08\times W$ and their yield displacement is taken to be 3cm. In total, 1,000 cantilever beam type dampers (Length: 65cm, Diame-ter:7cm,yield stress:9,000kg/cm^2, design horizontal displacement:about30cm) will be used.

Turning to the Soft Landing, the initial displacement δ_F is taken to be 5cm, and the friction coefficient μ is taken to be 0.2, then the overall friction stiffness K_F of the Soft Landing is 119,510t × 0.2/155cm = 154.2t/cm.

The analytical model of the base isolation device shown in Fig.15 divides the overall base isolation system consisting of rubber bearings, dampers, and Soft Landings into four sections, and distributes them at the four corners of the building.

Three models were studied and compared: (1) a model of the superstructure without base isolation device (Fixed-based model), (2) a base-isolated model equipped with rubber bearings and dampers, and (3) a base-isolated model provided with the above two devices plus Soft Landing.

Table 2 shows the eigenvalues of the three actual analytical models.

2) Establishment of design input seismic waves

Based on the seismicity, soil investigation, earthquake observation and the earthquake response characteristics of the ground at Tokai-mura site, we made artificial earthquake wave by using a target spectrum as shown in Fig.16. We assumed earthquake magnitudes and hypocenter to establish seismic waves which we considered to be the upper limit for a base isolation structure at that location. Fig.17 shows artificial TOKAI earthquake acceleration wave on ground surface. As a result the maximum acceleration is 428gal and the maximum velocity is 75kine on ground surface of Tokai wave.

The input waves were the recorded seismic waves, EL CENTRO NS waves and HACHINOHE EW waves, and artificial TOKAI wave. The input level was 50 kine, and we studied 75 kine as an excessive input.

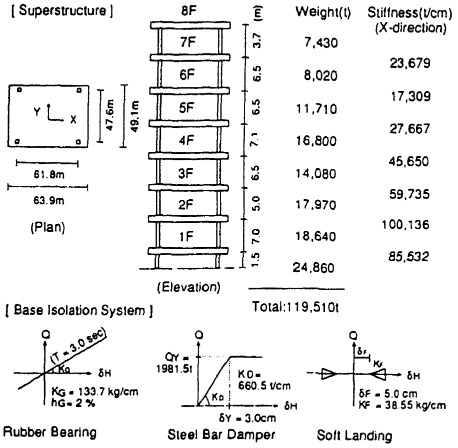


Fig.15 Actual Analytical Model

Table 2. Eigenvalues (Actual Analytical Models)

Mode No.	Fixed-based model	Base-isolated model (Rubber Bearing)	Base-isolated model (Rubber Bearing + Steel Bar Damper)
1	4.825 Hz	0.333 Hz	0.806 Hz
2	10.53 Hz	6.848 Hz	6.879 Hz
3	17.04 Hz	12.80 Hz	12.82 Hz
4	22.67 Hz	19.53 Hz	19.54 Hz
5	28.05 Hz	24.04 Hz	24.05 Hz
6	30.92 Hz	28.13 Hz	28.13 Hz
7	39.67 Hz	31.75 Hz	31.76 Hz
8	–	40.33 Hz	40.33 Hz

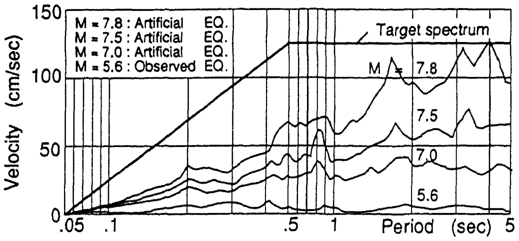


Fig.16 Response Velocity Spectrum

3) Earthquake response analysis

Table 3 show response acceleration and displacement obtained through the earthquake response analysis of each analytical model.

Fig.17 shows the response acceleration at the roof top of the fixed-based model under excessive input of TOKAI wave. Fig.18 shows the response accelerations at the rooftop and response displacements at the base isolation device in order to compare with effect of Soft Landing, while Fig.19 shows the restoring force characteristics of the base isolation devices under excessive input of HACHINOHE EW waves.

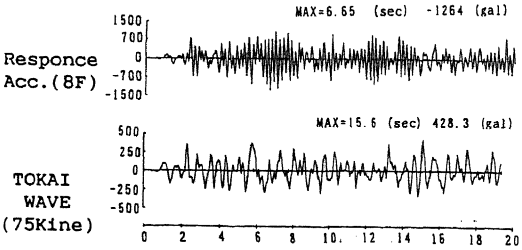


Fig.17 Response Analyses (Fixed-based Model

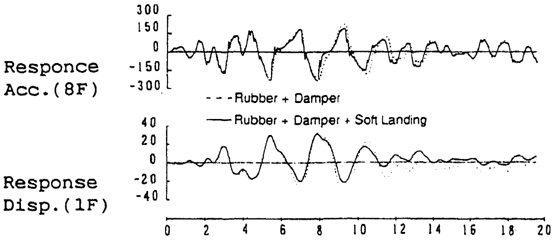


Fig.18 Response Analyses (Base-isolated Model)
(HACHINOHE EW Wave 75 Kine Input)

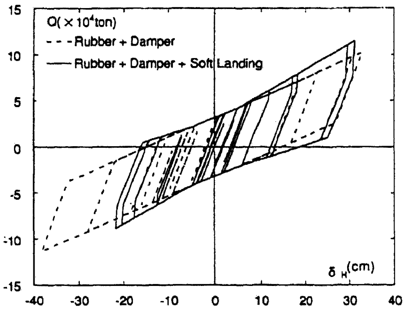


Fig.19 Hysteresis loop of base-isolation system (HACHINOHE EW Wave 75 Kine Input)

Table 3. The Maximum Values (Actual Analytical Models)

Analytical model	Input earthquake motion		EL CENTRO NS		HACHINOHE EW		TOKAI WAVE	
	Input velocity (kine)		50	75	50	75	50	75
	Input acceleration (gal)		510.8	766.2	255.4	383.1	285.5	428.3
Fixed-based model	Roof top (8F)	response acc. (gal)	1738.	2608.	879.0	1322.	842.9	1264.
		response disp. (cm)	1.85	2.78	1.06	1.59	0.999	1.50
Base-isolated model (Rubber Bearing + Steel Bar Damper)	Roof top (8F)	response acc. (gal)	135.6	187.8	156.7	225.6	151.2	205.9
		response disp. (cm)	15.69	25.91	19.97	38.70	22.05	30.73
	Base Isolation System (1F)	response acc. (gal)	133.5	183.7	154.6	223.7	149.6	203.5
		response disp. (cm)	15.49	25.63	19.73	38.36	21.82	30.42
Base-isolated model (Rubber Bearing + Steel Bar Damper + Soft Landing)	Roof top (8F)	response acc. (gal)	146.9	203.6	168.7	231.7	160.5	225.6
		response disp. (cm)	15.30	23.90	19.31	31.66	18.59	29.01
	Base Isolation System (1F)	response acc. (gal)	144.3	199.8	166.4	229.5	159.3	222.2
		response disp. (cm)	15.08	23.60	19.05	31.31	18.34	28.67

3 CONCLUSION

Based on the tests and analyses conducted on Soft Landing, the following results were obtained.

1. Soft Landing functions without applying large acceleration to the superstructure and reduces the deformation of the rubber

Comparing the results of these analyses reveals that the response acceleration of the base-isolated models is far lower than that of Fixed-based model. The comparison also indicates that adding the Soft Landing to the rubber bearing and damper base isolation system reduced the response displacement of the base isolation device without any significant amplification of the response acceleration. This was particularly the case with the HACHINOHE EW wave excessive input. The response displacement of the base isolation system with the rubber bearings and dampers was about 38 cm, which is almost identical with the rubber bearings design displacement of 40 cm. Adding the Soft Landing however, reduced the response displacement to about 31 cm, indicating that it can be relied on whenever raising the safety allowance of base isolation systems facing excessive input is needed.

bearing by sliding friction.

2. Soft Landing load-supporting function prevents buckling caused by the deformation of the rubber bearing.

3. The restoring force of the rubber bearing allows the superstructure to return to its original position, even after an excessive deformation.

4. Application to large nuclear fuel facility buildings confirms that a base isolation system incorporating the Soft Landing is expected to reduce seismic force, and guarantee safety even in the event of excessive input, and proves that the system can be applied as a safety device in actual facilities.

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