第二篇 结构减震技术
Part 2 Structural Vibration Control Technology

- 第2章 隔震结构设计

  Chapter 2 Design of isolation Structures
- 第3章 消能减震结构设计

  Chapter 3 Design of Energy-Dissipation Structures
- 第4章 结构被动控制技术

  Chapter 4 Structural Passive Control
- 第5章 结构主动、半主动控制技术

  Chapter 5 Structural Active and Semi Active Control

引　论 Introduction

- 结构减震控制的概念 The concept of Structural vibration control
- 1. 常规抗震抗风设计方法存在的问题 Problems in conventional design methods for seismic structure and wind resistant structure
  - 直接用承重结构抵御地震和风的作用

  Resist the earthquake and wind action directly by load-bearing structures
  - 用增加结构刚度的方法来满足抗风抗震要求，不经济

  Meet the requirement of earthquake and wind resistance by increasing structural stiffness, which is wasteful

引　论 Introduction

- 2. 结构振动控制方法的引入——减震控制 structural vibration control method
  - 对结构安装抗震装置，由抗震装置与结构共同承受地震作用，即共同储存和耗散地震能量，以减轻结构的地震反应。
    In order to reduce earthquake response, a seismic device is installed and resistant earthquake together with the structures by storing and dissipating earthquake energy

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=F(t)-[M][I]\ddot{x}_g$$

3 结构减震控制的分类 Types of vibration control

- 被动控制——不需要外部能源输入 Passive vibration control without energy input
  - 基础隔震：以改变结构频率为主的减震技术
  - Base isolation: changes the natural frequency of structure
  - 耗能减震：以增加结构阻尼为主的减震技术
  - Passive energy dissipation: increase structural damping
  - 被动质量调谐控制
  - Tuned mass damper

3 结构减震控制的分类 Types of vibration control

- 主动控制——需要外部能源输入提供控制力，控制力依赖于结构反应和外界干扰信号 active vibration control that require control force provided by energy input, which relies on structural response and disturbance signal
  - 控制系统由传感器、运算器和作动器组成 the control system consists of sensor, calculator and actuator
  - 缺点：造价昂贵，所需巨大能源在地震时无法保证 disadvantage: high-cost and the immense power required cannot be guaranteed during earthquake

半主动控制——采用可调参数的被动控制装置 semi-active control using passive control with adjustable parameters

- 不需要很大外部能源输入，依赖于结构反应和外界干扰信息，采用最优控制策略调整参数
- It relies on structural response and disturbance signal rather than large energy input and adopts optimal control strategy to adjust parameters
- 以被动控制为主，即具有被动控制的可靠性，又具有主动控制的适应性，是一种具有前景的控制技术 Mainly passive control, It is a promising control system which integrates the reliability of passive control and adaptability of active control

- 智能控制——采用智能控制算法和智能驱动或智能阻尼装置为标志的控制方式
intelligent control ------control method which adopts intelligent control algorithm, intelligent driver or intelligent damping device.
  - 智能控制算法 intelligent control algorithm
  - 智能材料和器件 intelligent material and device
- 混合控制——不同控制方式相结合的控制方法 Hybrid control---- that combines different control methods

- 结构减震控制
  - 被动控制
    - 基础隔震
    - 耗能减震
    - 吸振减震
  - 主动控制
    - 主动拉索
    - 主动支撑
    - 主动质量阻尼
    - 智能材料自控
  - 半主动控制
    - 变刚度半主动
    - 变阻尼半主动
    - 变刚度变阻尼半主动
  - 混合控制
    - 被动与主动混合
    - 被动与半主动混合
    - 半主动与主动混合

- 4. 优越性(与传统抗震结构对比) advantages over conventional aseismic structures
- 安全可靠（减震结构与传统抗震结构地震反应比值）Safety and reliability (the ratio of the earthquake response of damping structures to that of conventional aseismic structures)

  Isolation structures: 8%~25%

  Energy dissipation structures: 30%~60%

  TMD passive vibration control structures: 30%~60%

  Active control structures: 10%~50%

- 4.优越性（与传统抗震结构对比）

经济性好（节省工程造价）

economic efficiency (saving engineering cost)

vibration isolation structures:3%~20%

energy-dissipation structures: 3%~10%

passive or active control structures 5%~20%

- 建筑设计灵活 Flexible design
- 适应范围广 Wide range of applications
- 检测修复方便 Easy to maintenance

5. 工程结构减震控制技术的应用

减震控制技术的应用范围及成熟程度

名称	应用范围	技术成熟程度
隔震	1~30层，或高宽比不大于4的建筑物，要求确保地震中绝对安全的结构物、桥梁、设备等	安全可靠，明显有效减震，橡胶垫隔震技术较成熟
消能减震	水平刚度较小的多层，高层，超高层建筑，塔架，大跨度桥梁，管线等	安全可靠，有效减震抗风，技术较成熟
质量调谐	主振型较为明显稳定的多层，高层，超高层建筑，塔架，大跨度桥梁等	总体基本成熟，减震抗风视不同情况定
主动控制技术	对抗震抗风要求较高的建筑结构物	待完善
混合控制	各种不同类型，不同要求的建筑物	需合理组合，可达到有效减震抗风

5. 工程结构减震控制技术的应用 Applications of vibration control technology on engineering structures

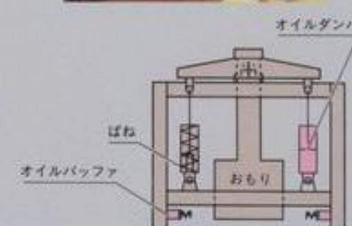
各ブレース部に取り付けられたハイダンパ

高層ビル制振用ハイダンパ

ビルのブレース部にハイダンパを取付けて揺れを小さくします。

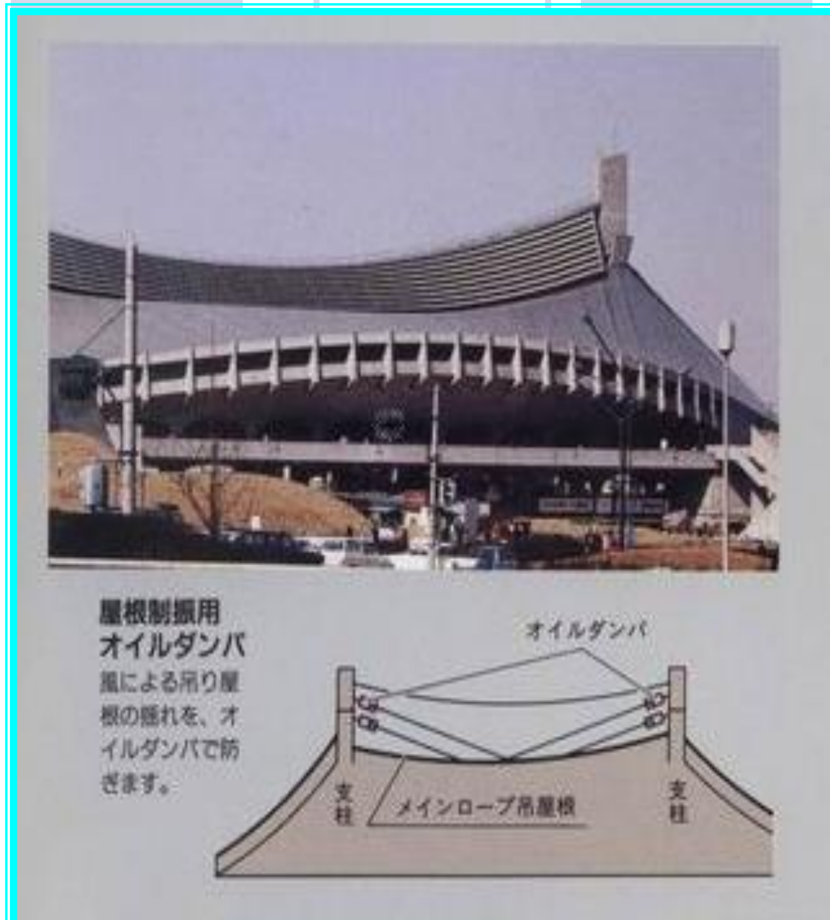
長大吊橋の制振装置(TMD)用オイルダンパ

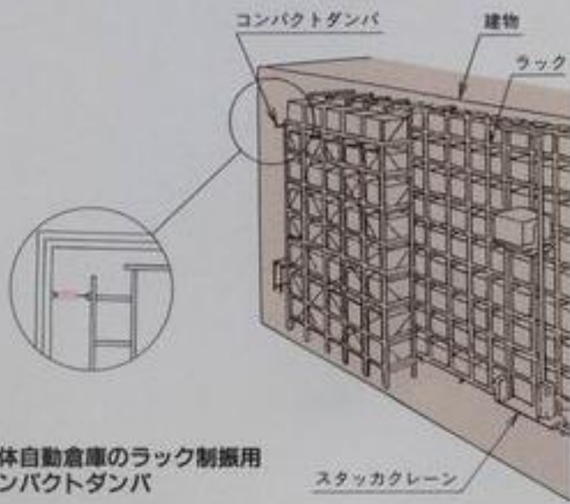
長大吊橋の主塔に設置されたオイルダンパ付、TMDの効果で、吊橋は地震や風の揺れに十分耐えられます。



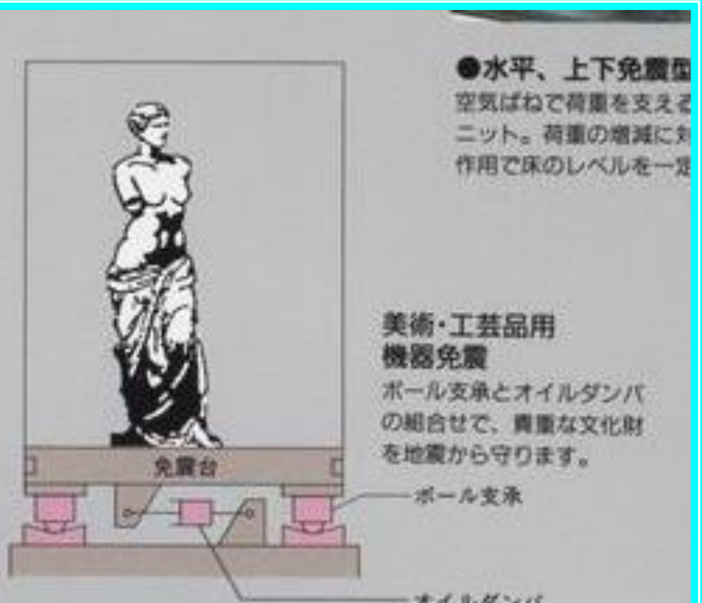
制振装置機構概念


制御装置設置階
高層ビル制振装置（AMD）用
オイルダンパ
高層ビルに設置された制振装置（AMD）には、フェールセイク機能として、オイルダンパが使われています。


屋根制振用
オイルダンパ
風による吊り屋根の揺れを、オイルダンパで防ぎます。
オイルダンパ
支柱
メインロープ吊屋根
支柱



立体自動倉庫のラック制振用
コンパクトダンパ



**美術・工芸品用
機器免震**

ボール支承とオイルダンパの組合せで、貴重な文化財を地震から守ります。

床免震用ボール支承

ボール支承の働きで、地震から床上の物を守ります。
大型コンピュータや美術・工芸品などを設置する部屋に適用されています。

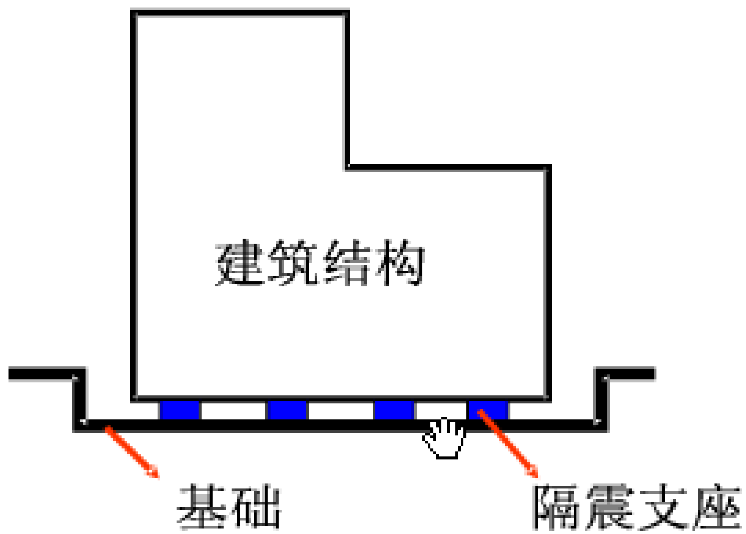
●水平免震型（２次元）

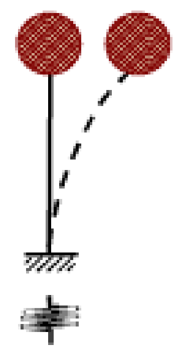
床用水平２次元免震型ユニットで、既存フロアのリフォームも可能です。住宅基礎にも利用できます。

●水平、上下免震型（３次元）

空気ばねで荷重を支える３次元免震型ユニット。荷重の増減に対しては調整弁の作用で床のレベルを一定に保ちます。

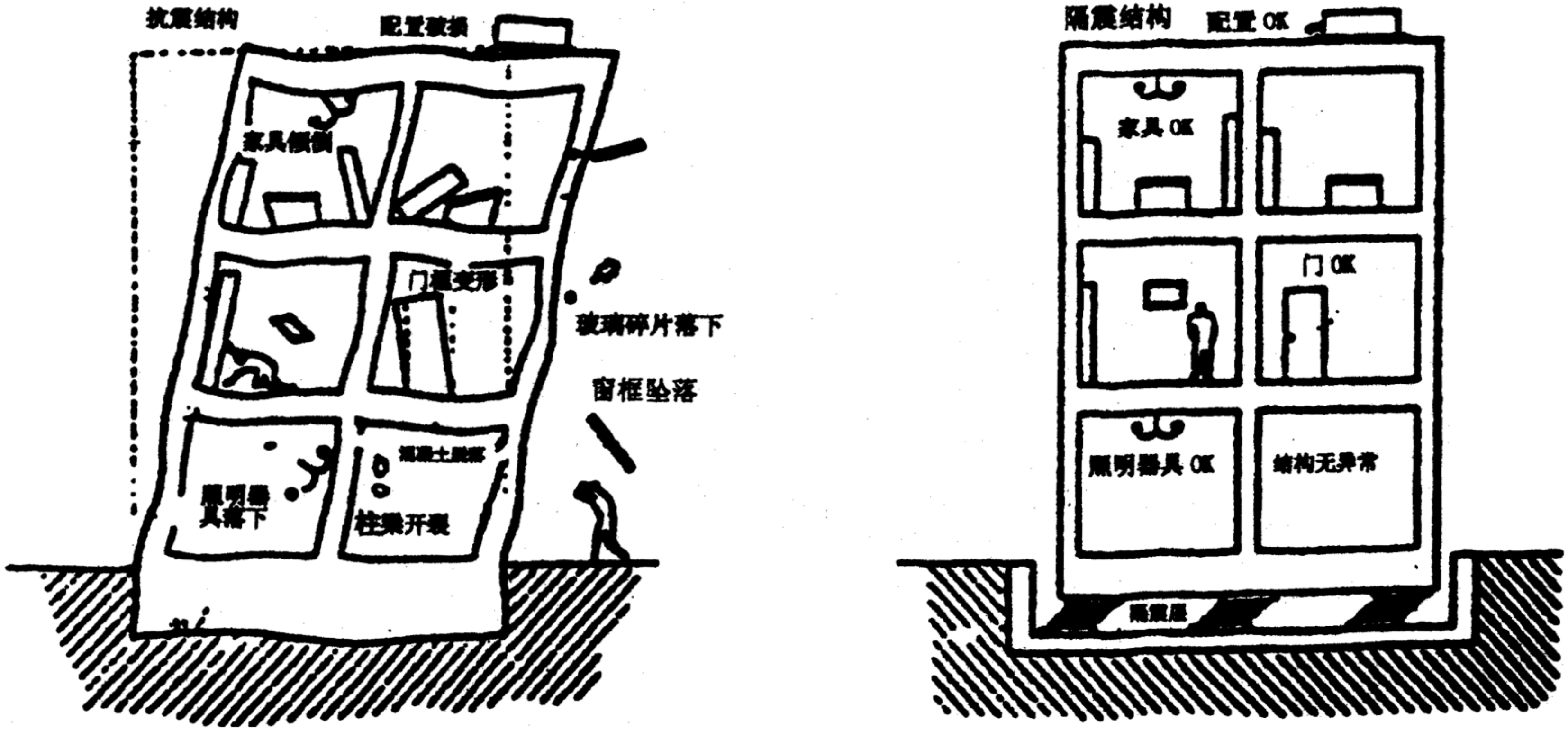
Chapter 2 Base isolation structure





隔震房屋是指在房屋底部与基础之间设置隔震层以隔离地震能量的房屋。

By using Isolators and dampers, the building is "decoupled" from the ground motion of any earthquake and the transmission of seismic energy to the building is dampened.


抗震结构
配置破损
家具倾倒
门框变形
玻璃碎片落下
窗框坠落
照明器具落下
柱梁开裂
隔震结构
配置 OK
家具 OK
门 OK
照明器具 OK
结构无异常
隔震层

隔震系统回顾
reviews of development in base isolation

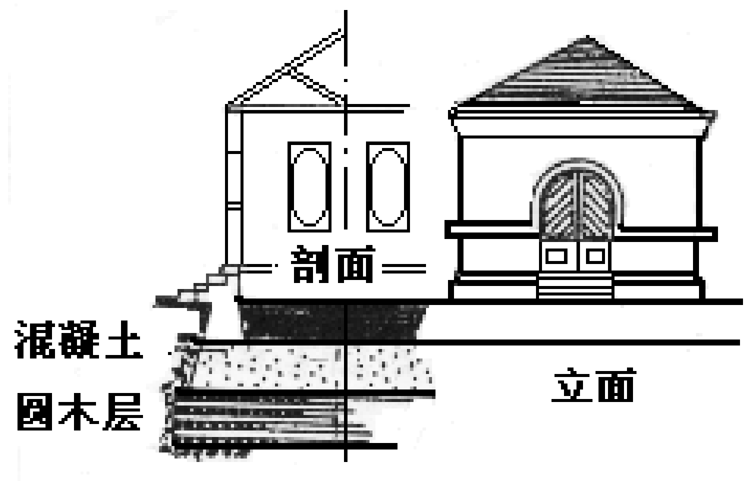
The idea of base isolation dates back to the late nineteenth century, but the application of generalized idea of base isolation has even longer history. The sticky rice mixed lime was used in the Forbidden Palace to form the flexible isolated layer. However the theory and application of modern base isolation just began in the 1970s and are widely used recently.

基础隔震的概念早在19世纪已有人提过，广义的隔震方案则更是源渊流长，如**北京故宫**就设有**糯米加石灰的柔性减震支座层**；现代的基础隔震理论和实践开始于上世纪70年代，应用较为广泛。

1.早期隔震技术 Early Seismic Isolation Technology

河合浩藏的“地震时不受大震动的结构”

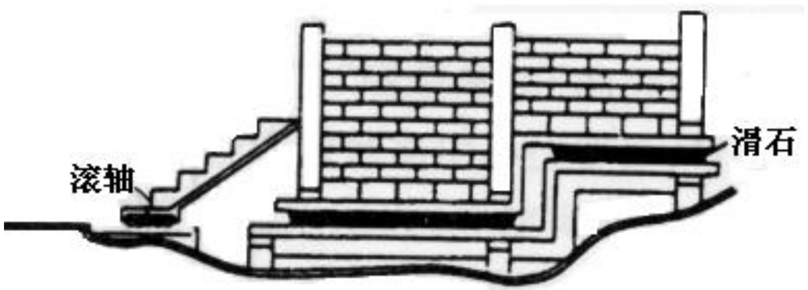
右图是1891年日本的河合浩藏的“地震时不受大震动的结构”。其隔震思路是在地基上并排铺设了数层圆木，并且把建筑物周围挖空，从而地震时可对上部建筑起到隔震作用



In 1891 Kawai Hirohide proposed the “structure without great vibration under earthquake”. The logs is used between the upper structure and base to isolate the building from the ground motion under earthquake.

Seismically isolated structures proposed by J.A.Calantarients

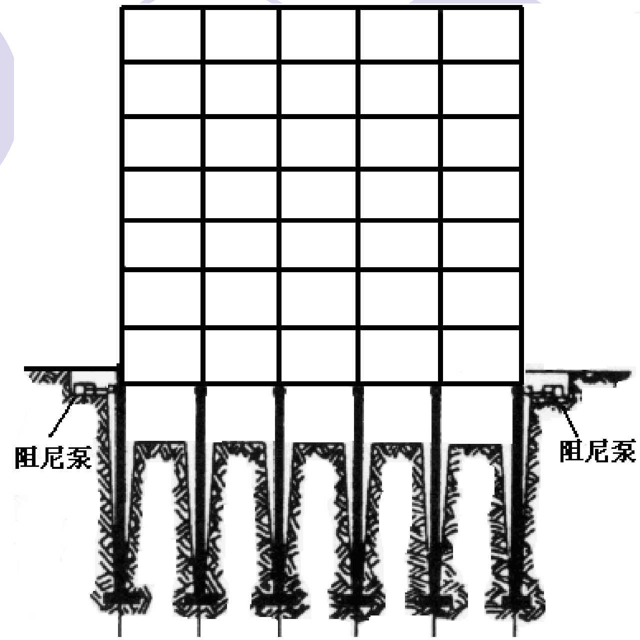
J.A.Calantarients于1909年提出的隔震结构(*Base-isolated building*)方案。这种隔震结构在建筑物结构与基础之间用滑石层隔开，地震时建筑物可以滑动。



The first patent application for seismic isolation was granted to Mr. J.A. Calantarients in 1909. His idea was to install a sliding layer between the building and its foundation to allow the building to slide during an earthquake. Thusly, the energy transmitted to the building itself is reduced

中村太郎的隔震结构

中村太郎于1927年提出的隔震结构方案。在这种隔震系统中已使用阻尼泵来耗散地震动的能量，并且在该建筑地下层柱的上下端采用铰接构造，建筑物可以水平自由移动。



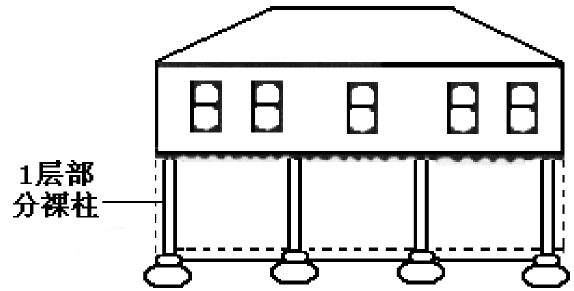
Nakamura Taro’s seismically isolated structures

In 1927, Nakamura Taro of Japan conceptually proposed a sleeved pile isolation system which was consisted of several columns under the ground floor slab with around 15 meters length to the depth of the soil under the structure and utilizing dampers at the joint points of ground floor slab and these columns.

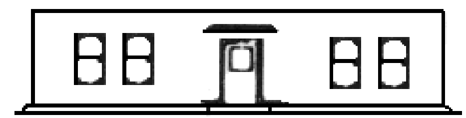
柔性层隔震结构(*Flexible first-story building*)

柔性层结构隔震概念由Martel在1929年提出，由Green(1935年)和Jacobasen(1938年)进一步加以研究与完善；左图是真岛健三郎于1934年的柔性层结构。地震时，柔性层进入塑性，结构的刚度变小，结构的基本周期延长，从而导致上部结构所受的地震作用减小。

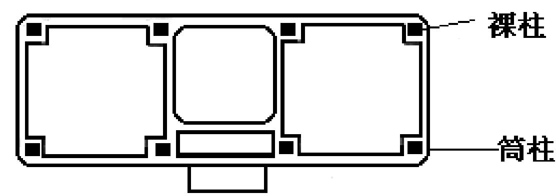
The concept of flexible first-story building was proposed by Martel in 1929 which was further improved by Green(1935) and Jacobasen(1938).The picture was this kind of building by Kenzaburo Mashima. During an earthquake, the flexible story becomes plastic, the stiffness reduced and structural period was extended, resulting in earthquake effect on the structure reduction.



立面图



1层立面图

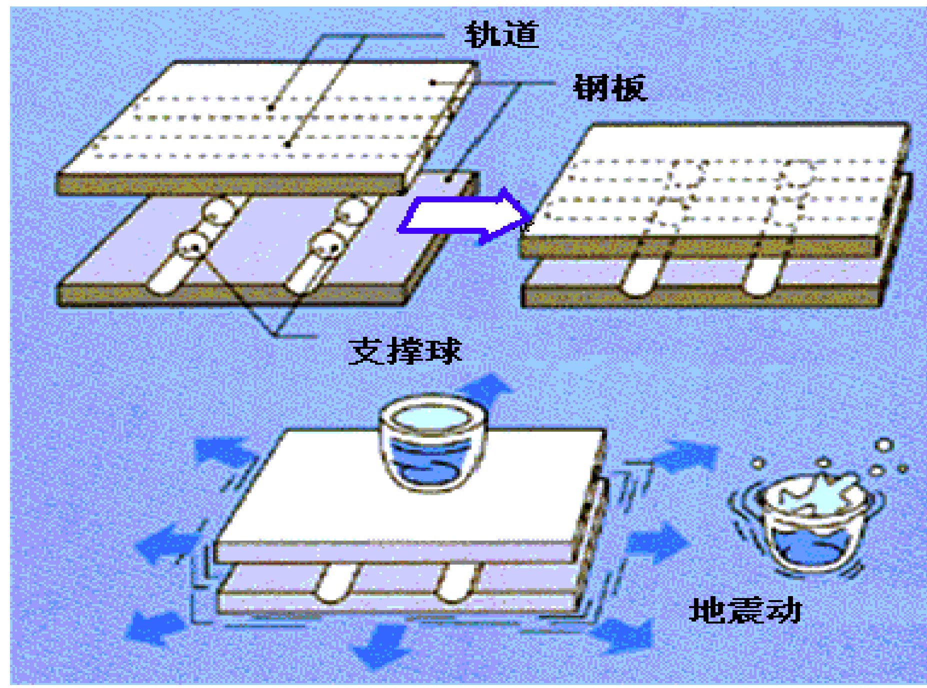


1层平面图

滚动支撑类隔震系统（*Roller bearing system*）

为克服柔性层结构所带来的缺陷，科学家们相继提出了多种滚动支撑类隔震系统，工作元件有球形和椭圆形等多种，但由于其隔震是有向的，而地震是具有无向性，这些类型的隔震系统均未能推广应用。

To overcome the defects of flexible first-story building, scientists proposed a variety of roller bearing systems including spheral and elliptic. However, because earthquake effect is isotropic, while the isolation of roller bearing systems is directional, this type of isolation failed in application



2. 现代隔震技术 modern seismic isolation technology

叠层橡胶支座隔震系统

The seismic isolation system—laminated rubber bearing

examples:

a. USC University Hospital

1994年1月17日，美国圣菲尔南多发生洛杉矶地震，震级M=6.7，直下型地震，死亡57人，伤8700人，损失很大。

The 1994 Northridge earthquake occurred on January 17, at 4:30:55 a.m. PST and its epicenter in Reseda, a neighborhood in the north-central San Fernando Valley region of Los Angeles, California. The blind thrust earthquake had a moment magnitude (Mw) of 6.7 and the death toll was 57, with more than 8,700 injured.

震中附近有两座医院，一座为隔震结构，另一座为抗震结构。

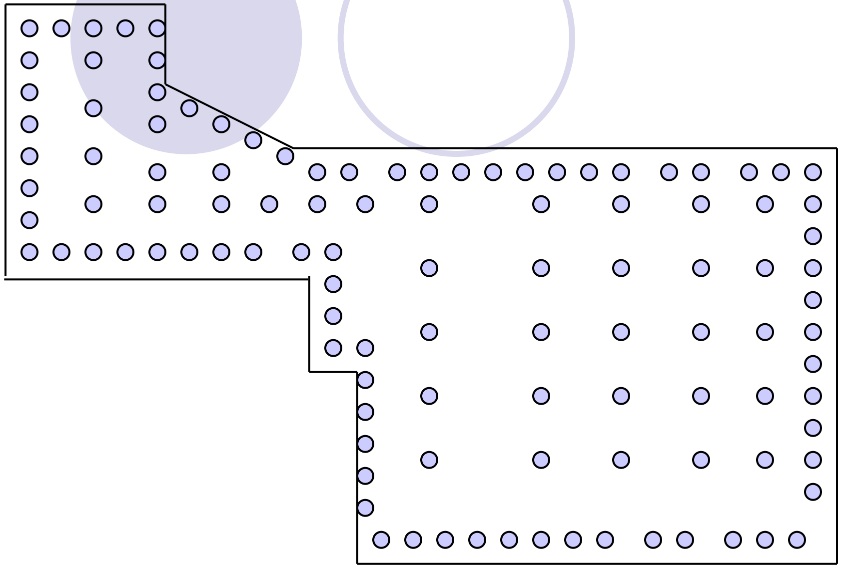
There were two hospitals near the epicenter. One is seismically isolation structure and the other is conventional seismic structure

中南加州大学医院（隔震结构）
In the 1971 San Fernando, California, earthquake (seismic isolation structure)

橄榄景医院（抗震结构）
The Olive View Hospital (conventional seismic structure)

南加州大学医院(*The University of Southern California Teaching Hospital*)是橡胶支座隔震系统，这栋七层医院基础加速度为0.49g，而顶层加速度只有0.21g, 加速度折减系数为1.8。而抗震结构橄榄景医院(*The Olive View Hospital*)的底层加速度为 0.82g，而顶层加速度为2.31g, 加速度放大系数为2.8，由此可见橡胶支座隔震系统的优越性。

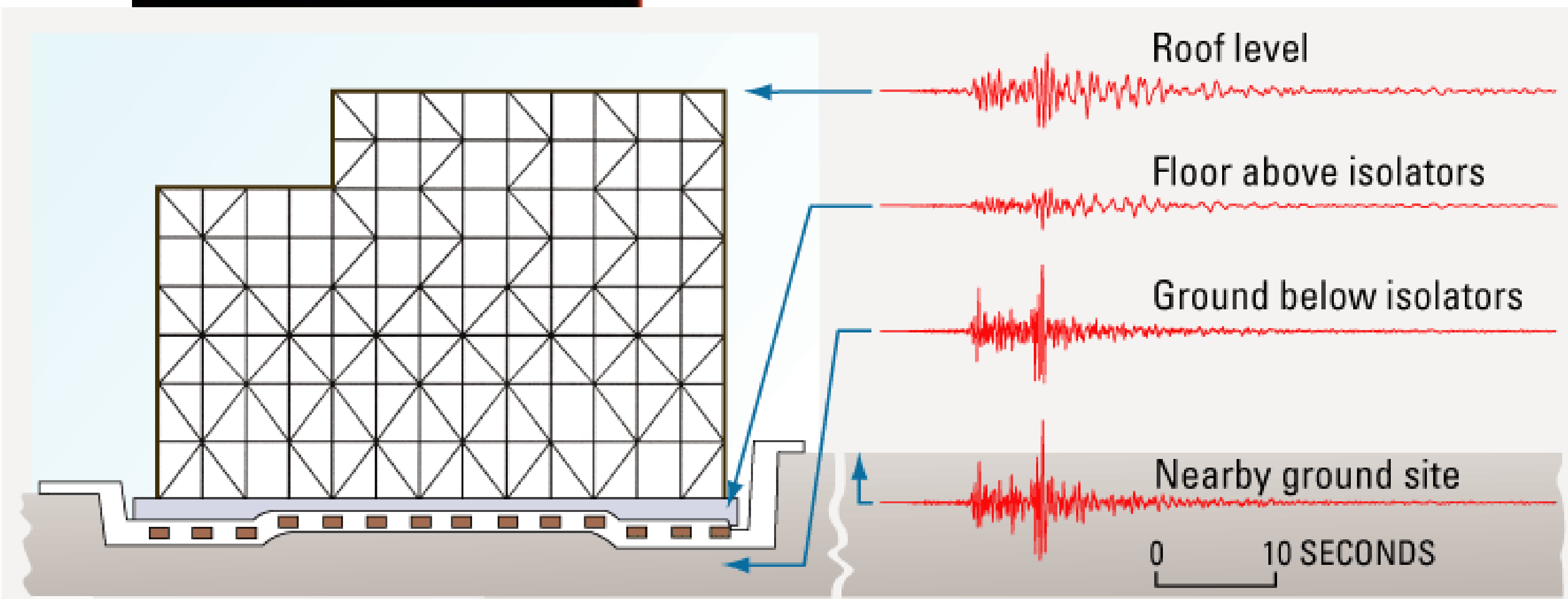
The hospital seismically isolated by a lead-rubber bearing system was able to continue to operate. This seven-storey hospital (the University of Southern California Teaching Hospital) underwent ground accelerations of 0.49g, while the rooftop acceleration was 0.21g, that is **attenuation** by a factor of 1.8. The Olive View Hospital, nearer to the epicenter, underwent a top floor acceleration of 2.31g compared with its base acceleration of 0.82g, a magnification by a factor of 2.8.



中南加州大学医院

地下一层，地上7层，建筑面积：33000平方米；占地：4100平米；最高高度：36.0m；铅芯多层橡胶隔震支座68个，多层橡胶隔震支座81个

The University of Southern California Teaching Hospital in eastern Los Angeles is an eight-story concentrically braced steel frame supported on 68 lead rubber isolators and 81 elastomeric isolators.



During the earthquake and following aftershocks, none of the 6-feet-height vases was knocked down and the medical instruments were undamaged. The hospital works properly and became a relief center playing an important role in the rescue.

橄榄景医院在1971年圣费尔南多地震中受到较大损害，10年后重建，并增加了抗震强度。
The Olive View Hospital suffered large damage In the 1971 San Fernando, California, earthquake and was rebuilt after 10 years with increased earthquake resistant strength

在此次地震中，剪力墙产生剪切裂缝，设备机器、医疗机械及家具等翻倒，病历等资料掉下、散乱。而且水管破裂，各层浸水，建筑物不能使用，完全丧失了医院的功能。
In the earth quake, the shear wall cracks, medical instruments and furniture fell, and medical records scattered on the ground.

橄榄景医院（抗震结构）
The Olive View Hospital (conventional seismic structure)

Moreover, the pipes burst and water flooded the layers. The building lost its function completely

b. 汕头八层框架结构商住隔震楼

1994年9月16日，台湾海峡发生了7.3级地震，震源距离汕头市约200公里，汕头市烈度为6度，各类房屋摇晃厉害，居民惊惶失措，无法站稳，青少年跳窗出逃，死亡126人；水桶里的水溅出了1/3左右……

而汕头市陵海路八层框架结构商住隔震楼上的人并没有感到晃动，听到毗邻楼房和邻街喧闹声后下楼才知道发生了地震。

The 1994 Taiwan earthquake occurred on September 16 in the southern Taiwan Strait, killing 126 people. The magnitude of this earthquake was given as Ms 7.3 by Fujian Seismological Bureau. The epicenter was located about 200 km from Shantou city. The Seismic intensity in Shantou is VI. Buildings shook and people panicked, barely standing on their feet. The Youth jumped out of window and water in buckets spilled out about 1/3.

However, People lived in the eight-story seismic isolated Frame structure at Linghai Road, Shantou felt nothing. Only after hearing cry and shouts nearby did they know there was an earthquake

c. WEST大厦（West Post Office Building）

1995年1月17日发生了日本阪神大地震。震级7.2级，是日本战后最大地震灾害。**在这次地震中，有二幢隔震建筑得到了地震观测记录。从这些记录可**看到隔震房屋在大地震中发挥了隔震效果，证实了隔震结构的有效性。WEST大厦(西部邮政大楼)建筑面积46000m²，6层，是日本最大的隔震建筑。该建筑距震源东北35公里，在基础、1层和6层进行了地震记录观测。

The Great Hanshin earthquake occurred on January 17, 1995 Japan. It measured 7.2 on the moment magnitude scale

The data on earthquake responses of two seismically isolated buildings was recorded. From the data we can clearly see the effectiveness of seismic isolation

West Post Office Building, which have six floor and two towers. It is 38.35m high and 46,000 square meters area. Isolation layer is disposed between the base and 1st floor and 6th floor

地震观测位置	方向		
	东西	南北	上下
6层	103	75	377
1层	106	57	193
基础	300	263	213

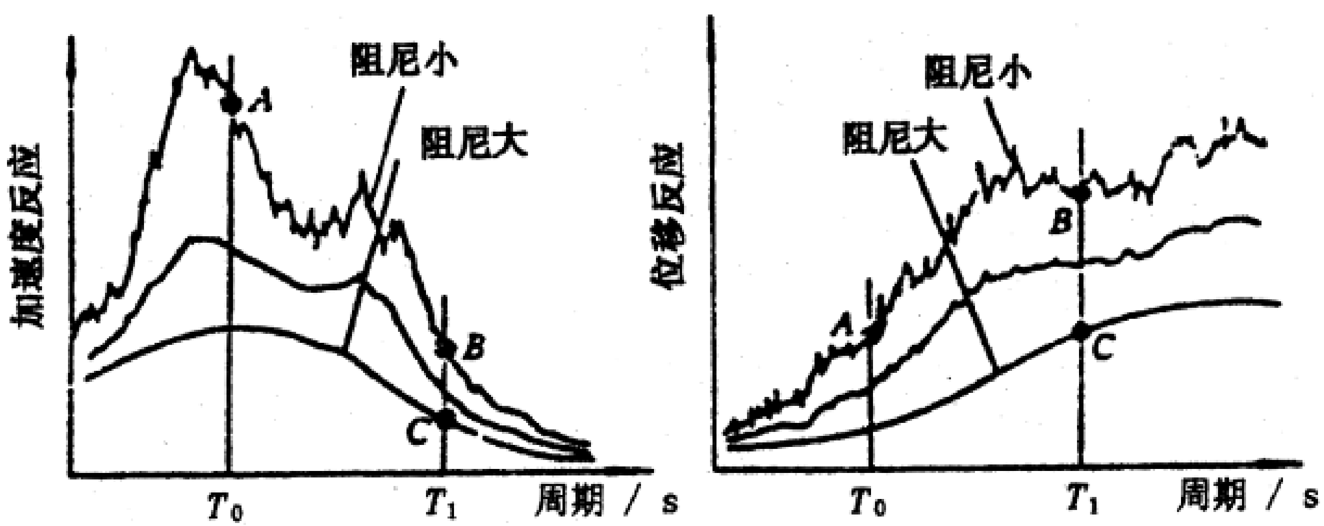
Chapter 2 Seismically isolated structure

2.1 结构隔震的原理与隔震结构的特点

2.1 Principles and characteristics of seismic isolation structure

2.1.1 结构隔震原理及基本特性

2.1.1 Principles and features of seismic isolation



设置隔震系统形成隔震层，延长结构的周期，增加结构阻尼，使结构的加速度反应减小，位移集中于隔震层，上部结构的振动接近于刚体，相对位移较小，结构基本处于弹性工作状态，不产生破坏或倒塌。

Mounting the structure on isolating layer can increases the natural period and damping of the structure, resonance and near-resonance are avoided and the seismic acceleration response is reduced.
The displacement mainly occurs in seismic-isolation layer.
The vibration of superstructure is similar to that of rigid body, and its layer relative displacement is limited. The structure works in the elastic stage without failure or collapse

隔震结构的基本特性
Basic features of seismically isolation

- 承载特性 Bearing capacity
  - 具有足够的竖向刚度和强度以支撑上部结构的重量。
  - Seismically isolated structures have sufficient vertical rigidity and strength to support the weight of superstructure
- 隔震特性 Seismic isolation
  - 具有足够的水平初始刚度，在风载和小震作用下，体系的水平位移极小，不影响使用要求；而中强地震时，其水平刚度较小，结构为柔性隔震结构体系。
  - With sufficient initial horizontal stiffness, the displacement of structure is minimum under wind load and small earthquake and does not affect serviceability. While in medium and strong earthquake, horizontal stiffness of structure is not enough and becomes flexible isolated system.

隔震结构的基本特性
Basic characteristic of seismically isolation

- 复位特性 Resetting
  - 地震后，上部结构能回复到初始状态，满足正常使用要求。
  - After earthquake, the superstructure can recover the original state to meet the serviceability requirement.
- 耗能特性 Energy dissipation
  - 隔震系统本身具有较大的阻尼，地震时能耗散足够的能量，从而降低上部结构吸收的地震能量。
  - Because seismic isolation system itself has large damping, and it can dissipate sufficient energy, thereby reducing the seismic energy absorbed by the superstructure.

2.1.2　隔震结构的特点及适用范围 advantages and Applicability of seismically isolated structure

- 隔震结构的特点 advantages of seismically isolated structure

（1）提高了地震时结构的安全性；

Increasing the safety of structure in earthquake

（2）上部结构设计更加灵活，抗震措施简单明了；

Flexible design of upper structure and concise seismic design

（3）防止内部物品的振动、移动、翻倒，减少了次生灾害；

Preventing the vibration, motion, and overturn of objects inside building, reducing secondary damage

（4）防止非结构构件的损坏；

Preventing damage to non-structural elements;

（5）抑制了振动时的不舒适感，提高了安全感和居住性；

Suppressing the discomfort in vibration and improving security and habitability

（6）可以保持机械、仪表、器具的功能；

Maintaining the functionality of machines, devices and appliances

（7）震后无需修复、具有明显的社会和经济效益；

No requirement for repair after earthquake, which has obvious social and economic benefits

（8）经合理设计，可以降低工程造价。

Reducing the project cost by reasonable design

隔震体系的适用范围

Applicability of seismic isolation system

（1）地震区2-30层的民用建筑。例如住宅、办公楼、教学楼、剧院等。

Civil buildings with 2 to 30 layers in earthquake zone such as residential building, office building, teaching building and theater.

（2）地震区的生命线工程。例如医院、急救中心、指挥中心、水厂、电厂、交通枢纽、机场等。

Lifeline projects in earthquake zone, including hospitals, emergency centers, command centers, waterworks, power plants, transportation hubs and airports

- 隔震体系的适用范围

Applicability of seismic isolation system

（3）地震区的重要建筑结构物。例如，重要历史性建筑、博物馆、重要纪念性建筑物、文物或档案馆、重要图书资料馆、危险品仓库等。

Important buildings in earthquake zone such as historical buildings, museums, ceremonial buildings, archives, libraries, storage of dangerous material, and so on.

（4）内部有重要设备仪器的建筑结构物。例如，计算机中心、精密仪器中心、实验中心、检测中心等。

Buildings containing important equipment and instruments, such as computer centers, centers of precision instruments, laboratories, and testing centers.

（5）桥梁、架空输水渠等重要结构物。

Important structures including bridges and aqueducts.

（6）放置重要历史文物、重要艺术珍品等的房屋或箱柜。

Buildings or cabinets containing important historical relics and art treasures.

（7）重要设备、仪器、雷达站、天文台等。

Important equipment and instruments, radar station and observatory.

（8）建筑物、结构物内部需特别进行局部保护的楼层。

Buildings and structures inside which special protection is needed locally

（9）已有的建筑物、结构物或设备、仪器、设施等不符合抗震要求者，可采用隔震技术进行隔震加固改良。

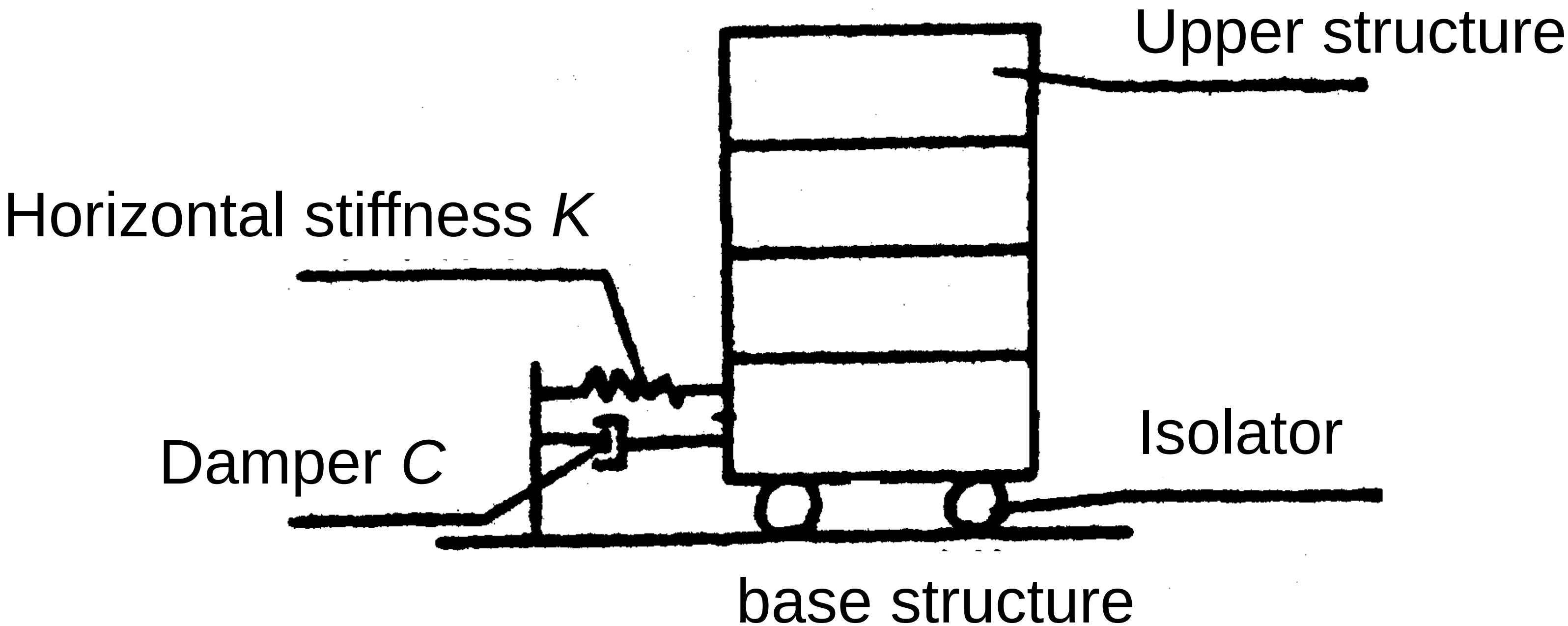
Existed buildings, structures, equipments, instruments, and facilities, that don’t meet the seismic requirement, can be improved by seismic isolation

2.2 隔震系统的组成与分类

components and classification of seismic isolation system

2.2.1 隔震系统的组成及各部件的作用

components of seismic isolated system and their functions



- **隔震系统的组成 components of seismic isolation system**

  隔震系统一般由隔震器、阻尼器、地基微震动或风反应控制装置等部分组成。

  Seismic isolation system generally consist of isolators, dampers and control device of structure vibration under wind or tiny ground motion

- **隔震器的主要作用： function of isolator**
- 支撑建筑物的竖向重量；在水平向具有弹性，能提供一定的水平刚度。延长结构基本周期，避开卓越周期，降低建筑物的地震反应。能提供较大的变形能力、自复位能力。常用的隔震器有：叠层橡胶支座，螺旋弹簧支座，摩擦滑移支座等

  Isolators have enough vertical stiffness to support the weight of the building, and have a considerable horizontal stiffness to increase the natural period of the building avoiding predominant period of ground motion, thereby reduce earthquake response. They also have large deformation capacity and self-resetting capacity. Common isolators: laminated rubber bearing, coil spring bearing, sliding bearing and other friction.

❖**阻尼器的主要作用： function of dampers**

吸收或耗散地震能量，抑制结构产生大的位移反应，同时在地震终了时帮助隔震器迅速复位。

Dampers absorb or dissipate earthquake energy and prevent structure from large displacement, and also help isolators to reset quickly after earthquake.

❖**地基微震动与风反应控制装置的主要作用：**

❖增加隔震系统的初期刚度，使建筑物在风荷载或轻微地震作用下保持稳定。

Increase the initial stiffness of the isolation system, and maintain the stability of the buildings under pulsation of the ground and the wind load

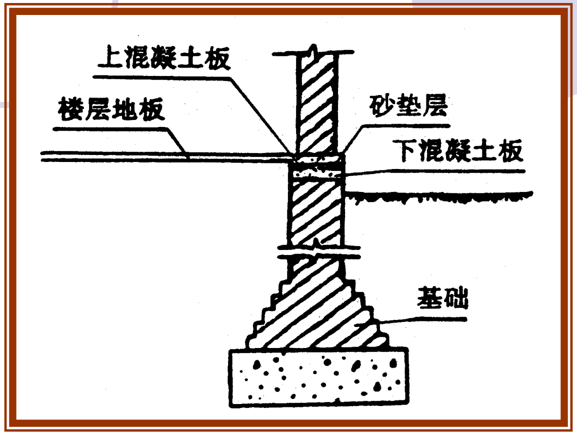
2.2.2 隔震系统的分类 Types of seismic isolation system

（1）弹性支承式隔震 Elastomeric bearing seismic isolation

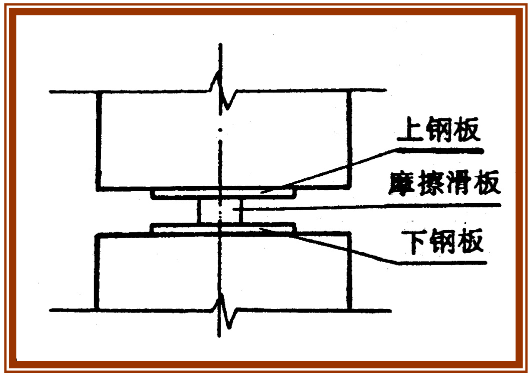
（2）滑移式隔震 Sliding seismic isolation

（3）摆动式隔震 swaying seismic isolation

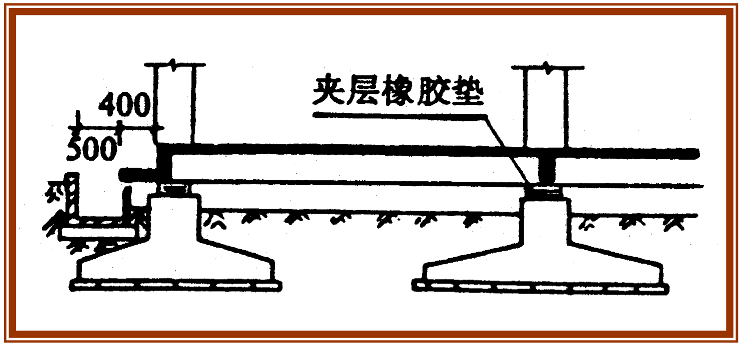
（4）悬吊式隔震 suspending seismic isolation



砂粒滑移层隔震房屋



摩擦滑块（板）房屋



夹层橡胶垫隔震房屋

叠层橡胶支座的构造与性能

configuration and properties of laminated rubber bearing

叠层橡胶支座是由**薄橡胶和薄钢板分层交替叠合**，经高温高压硫化粘结而成。

Laminated rubber bearing was consist of thin rubber and steel plates laminated alternately and glued together after high temperature and high pressure vulcanization.

橡胶支座形状可以为圆形、方形或矩形，一般多为圆形，因圆形与方向无关。支座中心一般设有圆孔，以使硫化过程中橡胶支座所受热量均匀，从而保证产品质量。

Rubber bearing shape may be circular, square or rectangular, and more generally circular, because its mechanical property is independent of direction. There is generally a hole in the center of the bearing, so it can be heated evenly during vulcanization, thus ensuring product quality.

- **`普通叠层橡胶支座 common laminated rubber bearing**

  具有弹性性质，但本身并无显著的阻尼性能。

Being elastic but not having significant damping property

- **铅芯叠层橡胶支座 Lead rubber bearing**

  灌入铅棒的目的：一是提高支座的吸能效果，确保支座有适度的阻尼；二是增加支座的早期刚度，对控制风反应和抵抗地基的微振动有利。灌入铅棒的直径根据设计要求通过计算确定。

The purpose of lead plug in the rubber bearing:

to improve bearing's energy-absorbing capability and ensure that is has moderate damping;

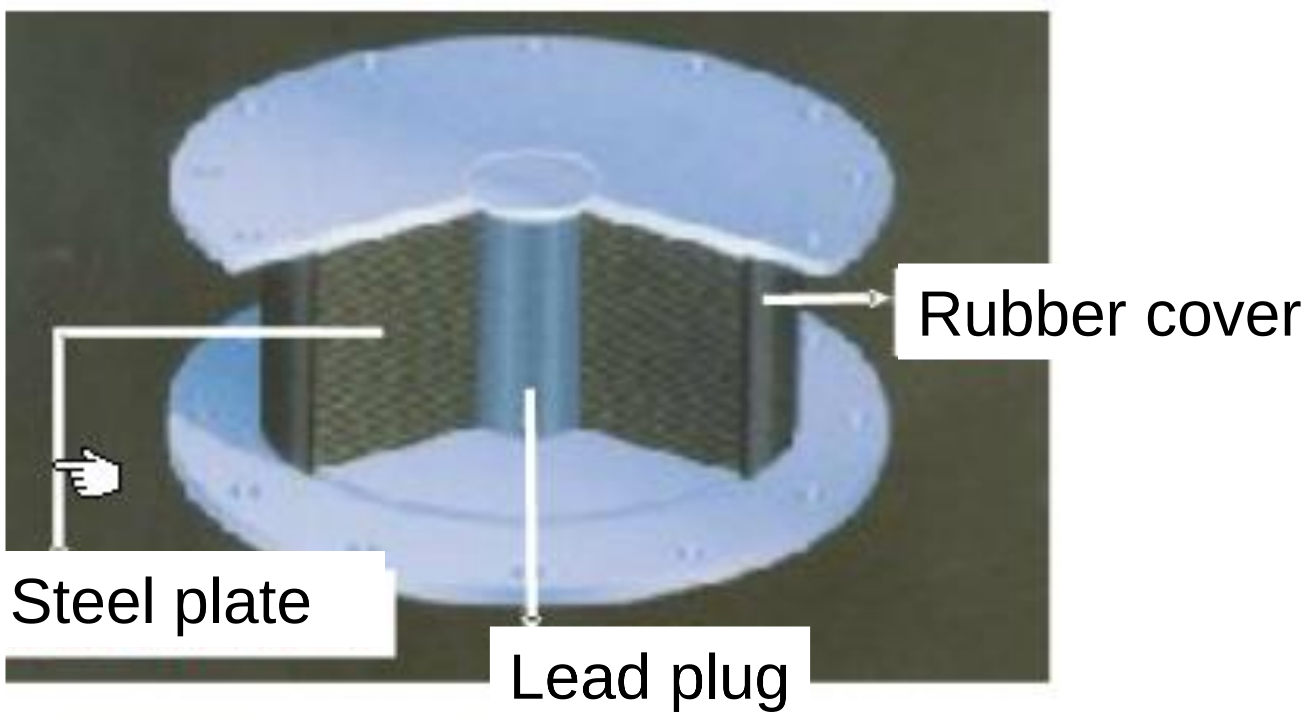
to increase the early stiffness of bearings which is helpful for controlling wind-induced response and the icro vibration by micro motion of foundation.

- **高阻尼叠层橡胶支座 High damping laminated rubber bearing**

　　采用高阻尼橡胶材料制造，可以根据高阻尼橡胶材料中石墨的掺入量来调节材料的阻尼特性。高阻尼橡胶也可以是高分子合成材料，这种人工合成橡胶不仅性能好，抗劣化性能也极佳。

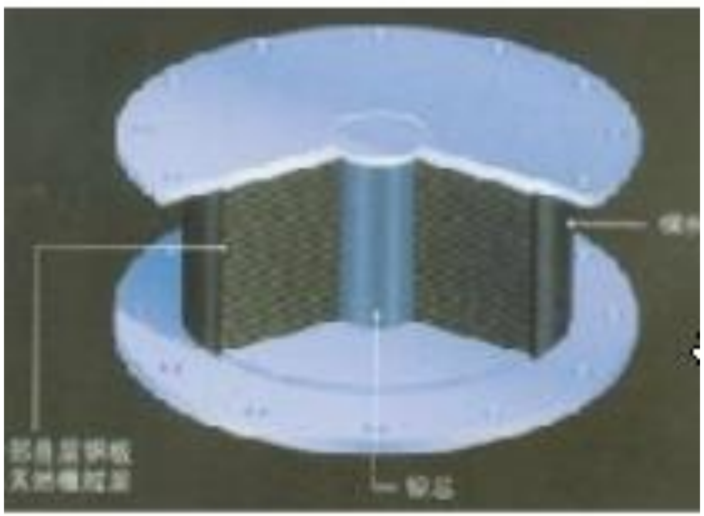
the damping characteristics can be adjusted by the amount of graphite mixed in the high damping rubber material. The high damping rubber may also be a synthetic polymer material. This kind of synthetic rubber has not only good performance but also perfect anti-degradation ability.

Configuration of lead rubber bearing



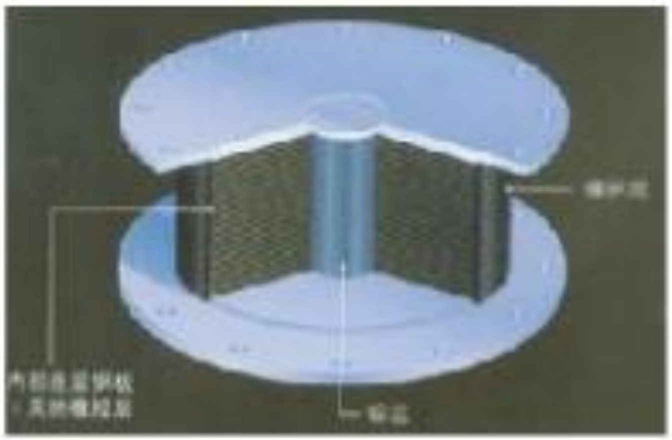
Mechanical behavior of lead rubber bearing

①compression behavior: same with the compression strength of same- sized RC column



Due to the difference of the elastic constants between the two materials, the steel plate constraints the lateral deformation of rubber make it under three-direction compression, so its vertical compression capacity is much greater than that of rubber.

② tensile behavior



tensile strength depends on the tensile strength of rubber

tensile strength depends on the tensile strength of rubber. It tensile elastic stiffness is only one tenth of compression stiffness. The experiment also shows: the stiffness under compression after large tensile deformation reduces by a half of initial stiffness.

③ durability: same with that of building

- The durability of rubber bearing is dependant of rubber which is affected by the creep and oxidation reaction. Because the steel laminated with rubber, the rubber surface exposed in air is limited that the internal rubber isn’t degraded even the surface has been oxidized.
- The investigations and observation on a 100-years rail rubber bearing isolators verified the results.
- Furthermore, experiments results shows than the creep thickness of rubber is only 10% of the total rubber thickness in bearing.
- Therefore the durability is consistent of the service-life of building.

Configuration and details of lead rubber bearing

Isolators in bridge

- 作业：
- 选择一种隔震系统（弹性支撑式、滑移式、摆动式、悬吊式等），从其历史发展，构造特点、耗能特点、工程应用及局限性，甚至国内主要厂家等方面进行阐述，并分组展示。

2.3　基础隔震结构动力反应分析

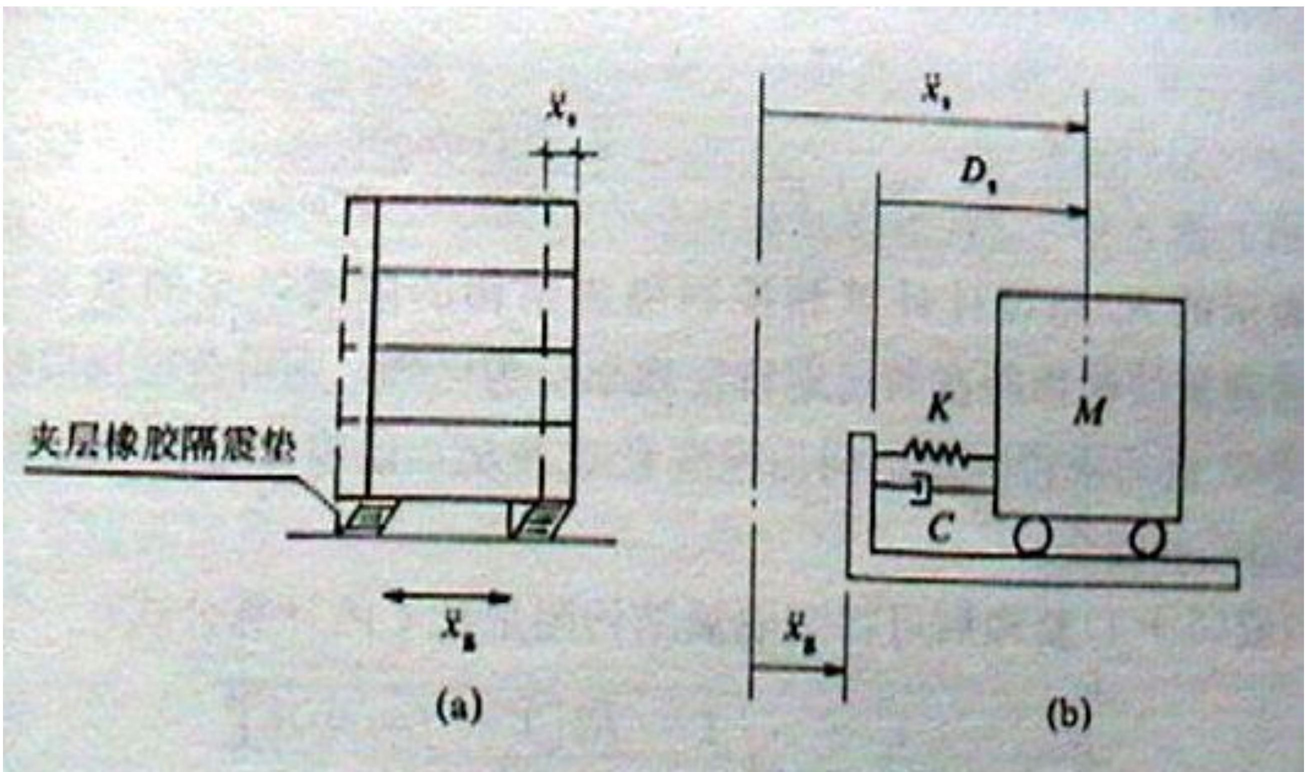
Dynamic response of base-isolated structures

2.3.1 单质点基础隔震体系结构动力分析

Dynamic Response of SDOF base-isolated systems

隔震结构动力分析模型

dynamic model of seismically isolated structures



加速度反应分析 Acceleration response

动力方程 Equations of motion

$$M\ddot{x}_s + C\dot{x}_s + Kx_s = C\dot{x}_g + Kx_g \qquad (2\text{-}1)$$

$$\ddot{x}_s + 2\zeta\omega_n\dot{x}_s + \omega_n{}^2 x_s = 2\zeta\omega_n\dot{x}_g + \omega_n{}^2 x_g$$

求结构体系的加速度反应 $\ddot{x}_s$，可采用转换函数的方法。设结构体系的加速度反应转换函数为H(ω)；地震地面的场地特征频率为ω；地面地震加速度 $\ddot{x}_g = e^{iwt}$；

则隔震结构地震 加速度反应 $\ddot{x}_s = H(\omega)e^{i\omega t}$

the acceleration response of the structure $\ddot{x}_s$ can be analyzed by transform function. If the transmission function of the acceleration response of the structure is H(ω), the characteristic site frequency be ω, and the seismic ground acceleration be $\ddot{x}_g = e^{i\omega t}$. Thus the ground acceleration response of the seismic-isolation structures is $\ddot{x}_s = H(\omega)e^{i\omega t}$

- **加速度反应分析** Acceleration response
- **动力方程** Equations of motion

把 $\ddot{x}_g$ 及 $\ddot{x}_s$ 代入式（2-1），经过整理归纳，可得到隔震结构体系的加速度反应转换函数为：

Substitute $\ddot{x}_g$ and $\ddot{x}_s$ into equation (2-1),the transmission function of acceleration of seismic-isolation structures can be solved.

$$H(\omega)=\frac{\ddot{x}_s}{\ddot{x}_g}=\sqrt{\frac{1+(2\zeta\omega/\omega_n)^2}{[1-(\omega/\omega_n)^2]^2+(2\zeta\omega/\omega_n)^2}} \qquad （2\text{-}2）$$

$$H(\omega)=\frac{\ddot{x}_s}{\ddot{x}_g}=\sqrt{\frac{1+(2\zeta\omega/\omega_n)^2}{[1-(\omega/\omega_n)^2]^2+(2\zeta\omega/\omega_n)^2}}$$

物理意义：地震时隔震结构的地震加速度反应与地面地震加速度之比值。反映隔震结构对地面地震加速度的衰减效果。

The transmission function is the ratio of acceleration response of the seismic-isolated structures to the ground acceleration. It reflects the damping effect of the ground acceleration by the seismic-isolation.

- 加速度反应衰减比R_a
- attenuation ratio of acceleration response

$$R_a=\frac{\ddot{x}_s}{\ddot{x}_g}=\sqrt{\frac{1+(2\zeta\omega/\omega_n)^2}{[1-(\omega/\omega_n)^2]^2+(2\zeta\omega/\omega_n)^2}} \qquad （2\text{-}3）$$

R_a是设计计算和控制隔震结构的隔震效果的重要基本公式。

- 隔震结构阻尼比

整理式(2-3）得到隔震结构阻尼比的计算公式：

From the formulas (2-3), the damping ratio of seismic-isolation structures can be obtained:

$$\zeta = \frac{1}{2(\omega/\omega_n)}\sqrt{\frac{1-R_a{}^2[1-(\omega/\omega_n)^2]^2}{R_a^2-1}} \qquad （2\text{-}4）$$

隔震结构位移反应 Displacement response

动力方程 Equations of motion

$$M\ddot{D}_s + C\dot{D}_s + KD_s = -M\ddot{x}_g$$

$$\ddot{D}_s + 2\zeta\omega_n\dot{D}_s + \omega_n{}^2 D_s = -\ddot{x}_g \qquad (2\text{-}5)$$

求结构体系的加速度反应 $\ddot{x}_s$，可采用转换函数的方法。设结构体系的位移反应转换函数为G(ω)；地震地面的场地特征频率为ω；地面地震加速度 $\ddot{x}_g = e^{iwt}$，

则隔震结构地震位移反应 $\ddot{x}_s = G(\omega)e^{i\omega t}$

the acceleration response of the structure $\ddot{x}_s$ can be analyzed by transform function. If the transmission function of the dynamic response of the structure is G(ω), the characteristic site frequency be ω, and the seismic ground acceleration be $\ddot{x}_g = e^{i\omega t}$. Thus the ground acceleration response of the seismic-isolation structures is $\ddot{x}_s = G(\omega)e^{i\omega t}$

Similarly the transmission function of displacement and the amplifying coefficient are obtained

$$G(\omega)=\frac{D_s}{\ddot{x}_g}=\frac{1}{\omega_n^2}\sqrt{\frac{1}{[1-(\omega/\omega_n)^2]^2+(2\zeta\omega/\omega_n)^2}} \qquad (2\text{-}6)$$

$$|D_s|=\frac{|\ddot{x}_g|}{\omega^2}\sqrt{\frac{1}{[1-(\omega/\omega_n)^2]^2+(2\zeta\omega/\omega_n)^2}} \qquad (2\text{-}7)$$

Eq.(2-7) is used to calculate the absolute maximum of displacement of isolation layer

The value $|D_s|$ is dependant of the acceleration of ground motion, characteristic site frequency, the frequency ratio ω/ω_n and damping of isolated layer. Generally the $|D_s|$ can be reduced by increasing the damping of isolated layer.

Defined R_d as the magnification factor of displacement response of isolation structure.

$$R_d = \frac{D_s}{D_g} = \frac{1}{\omega_n^2}\sqrt{\frac{1}{[1-(\omega/\omega_n)^2]^2+(2\zeta\omega/\omega_n)^2}} \qquad (2\text{-}8)$$

$$D_g = \frac{|\ddot{x}_g|}{\omega_n{}^2}$$

R_d：表征隔震装置位移放大效应的指标。当场地特性（ω）与隔震装置的刚度特性（K或ω_n）已定时，可通过增大隔震装置的阻尼比ξ来减少隔震装置的水平变位。

R_d is the index of the displacement magnification of isolators, if the site is given, the stiffness of isolated layer is determined, the damping of isolator can be adjusted to reduce the horizontal deformation.

2. 3. 2 Dynamic response of MDOF isolation structure

- **Dynamic model of MDOF isolation structure**

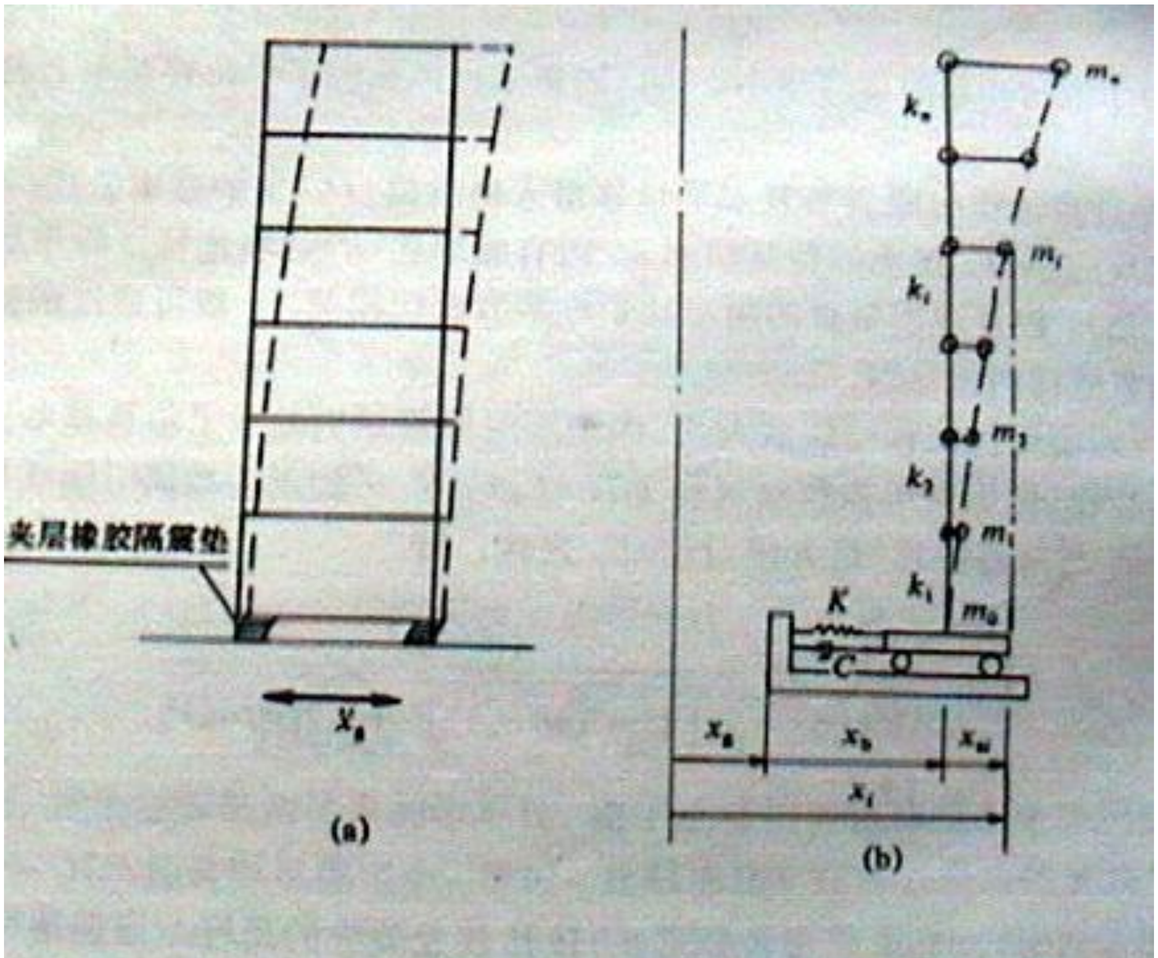


图 5-2-1 多质点平动体系基础隔震结构动力分析模型

- **Equation of motion for MDOF structure under earthquake**

$$\left[m\right]\left\{\ddot{x}_s\right\}+\left[C\right]\left\{\dot{x}_s\right\}+\left[K\right]\left\{x_s\right\}=-(\ddot{x}_g+\ddot{x}_b)\left[m\right] \qquad (2\text{-}9)$$

If the frequency eigenvalue matrix of structure is [ω]=diag{ω_1^2 ,ω_2^2, ω_3^2,…, ω_n^2}; the shape eigenvector matrix is [Φ], then the Generalized coordinates is introduced {q}, which is a function of time, therefore the displacement response can be expressed as:

$$\{x_s\}=[\Phi]\{q\} \qquad (2\text{-}10)$$

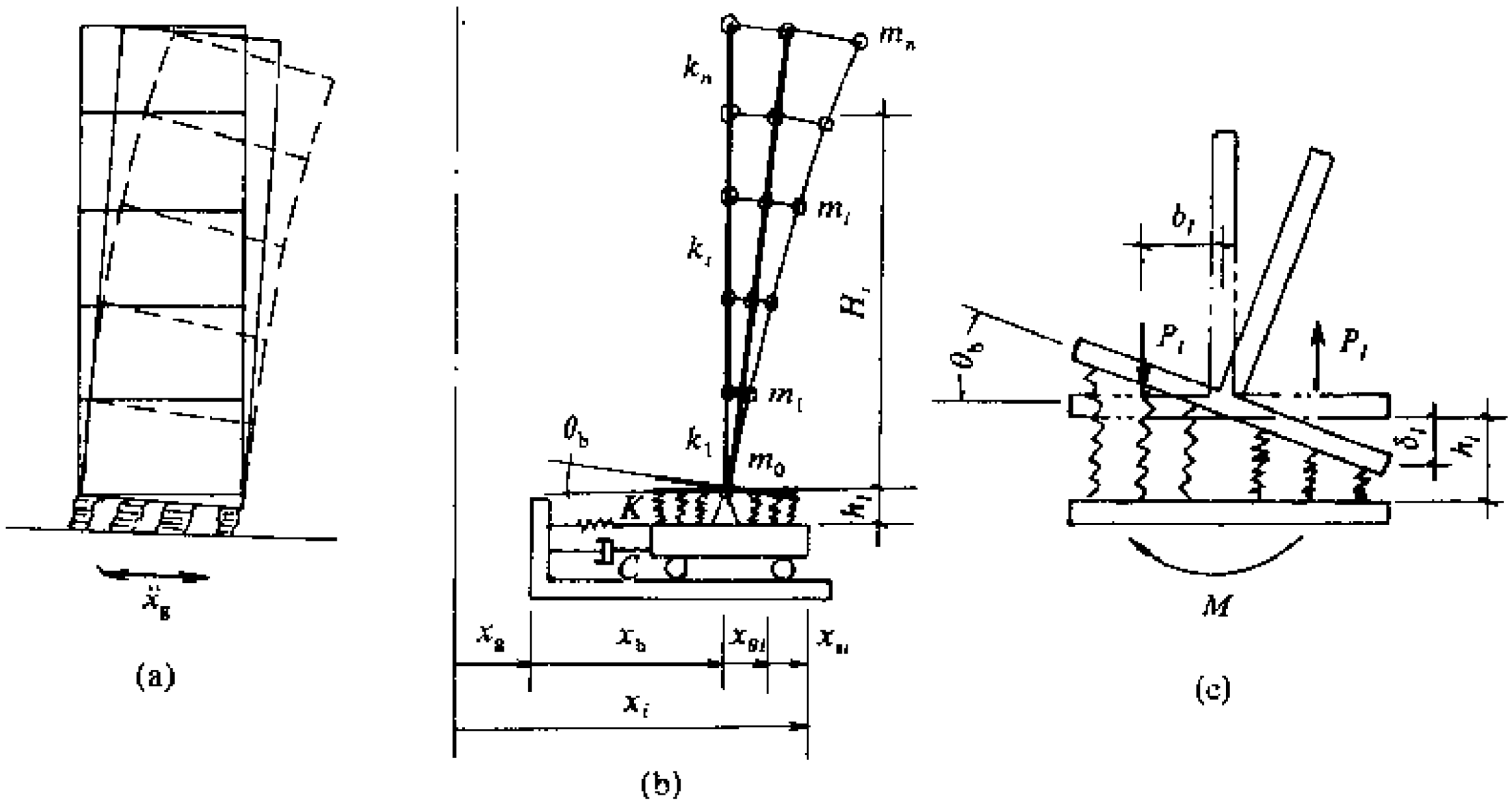
Substituting the eq.(2-10) into eq.(2-9), and multiplying the $[\Phi]^T$ on both sides of the equation

$$[\Phi]^T\left[m\right][\Phi]\{\ddot{q}\}+[\Phi]^T\left[C\right][\Phi]\{\dot{q}\}+[\Phi]^T\left[K\right][\Phi]\{q\}=-(x_g+x_b)[\Phi]^T\{m\}$$

Because of the Modal orthogonality, the above equation can be simplified as:

$$\left[I\right]\{\ddot{q}\}+\left[C^*\right]\{\dot{q}\}+\left[\omega\right]\{q\}=-(\ddot{x}_g+\ddot{x}_b)\left[\Phi\right]^T\{m\}$$

- Dynamic model of MDOF Horizontal and swing system
- 多质点平摆动体系结构动力分析模型



2.3.3 analysis and control on isolation effect of base isolation structure

control parameters

（1） attenuation ratio of acceleration response

$$R_a = \frac{\ddot{x}_s}{\ddot{x}_g} = \sqrt{\frac{1+(2\zeta\omega/\omega_n)^2}{[1-(\omega/\omega_n)^2]^2+(2\zeta\omega/\omega_n)^2}}$$

（2)Damping ratio

$$\zeta = \frac{1}{2(\omega/\omega_n)}\sqrt{\frac{1-R_a{}^2[1-(\omega/\omega_n)^2]^2}{R_a^2-1}}$$

（3） magnification factor of displacement

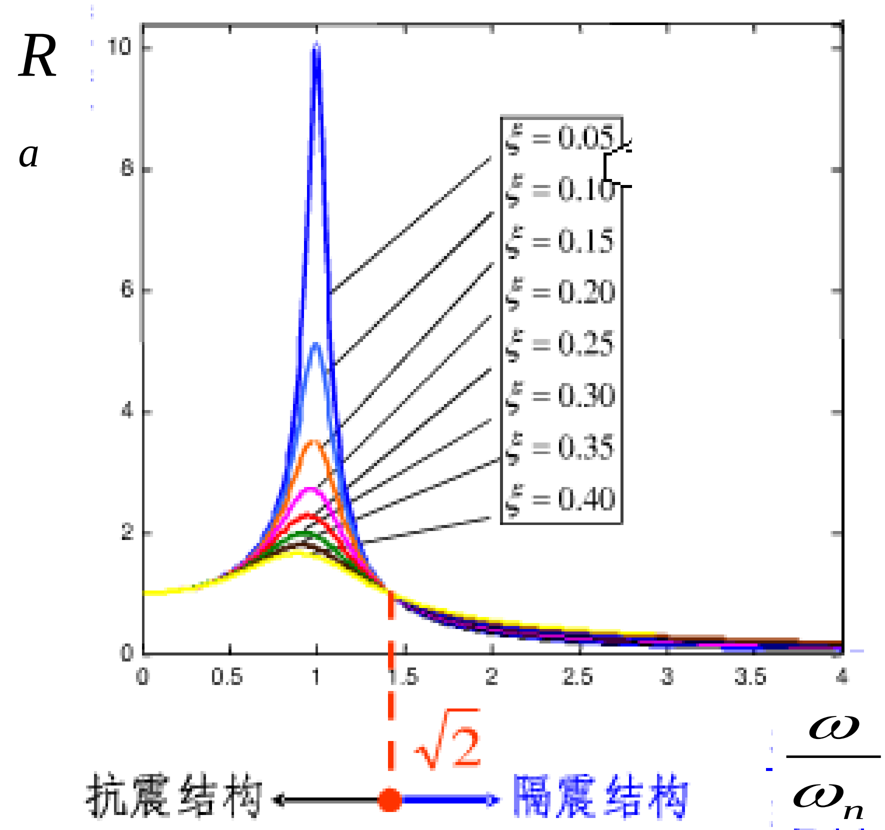
$$R_d = \frac{D_s}{D_g} = \frac{\omega^2}{\omega_n^2}\sqrt{\frac{1}{[1-(\omega/\omega_n)^2]^2+(2\zeta\omega/\omega_n)^2}}$$

- 隔震结构与传统抗震结构的理论分界线
- The theoretical boundary between seismic-isolation structures and the conventional seismic structures

Given $R_a = \dfrac{\ddot{x}_s}{\ddot{x}_g} = 1$

the frequency ratio $\omega/\omega_n = \sqrt{2}$.

That is, any damping ratio of structure can't isolate seismic action when the $\omega/\omega_n = \sqrt{2}$, which is the theoretical boundary value of the isolation structure and conventional seismic structure, which is marked as A in right graph.



结构的加速度反应与频率比的关系

- 基础隔震结构的隔震效果分析 Effect of base isolation structures for the laminate rubber bearing isolation structure， if its damping ratioζ=0.1 ~0.3， and frequency ratio ω/ω_n=2.5~4.5, then：

$$R_a = \frac{\ddot{x}_s}{\ddot{x}_g} = 0.06 \sim 0.33$$

for the conventional seismic structure：$\ddot{x}_s / \ddot{x}_g > 2$

for the base-isolation structure：

$$\ddot{x}_{s(g)} / \ddot{x}_{s(c)} \leq (0.06 \sim 0.33)/2 \leq 0.03 \sim 0.165 = 1/33 \sim 1/6$$

当发生地震时，隔震结构的地震反应仅为传统抗震结构的地震反应的1/33-1/6,相当于降低地震烈度约2.5-5度。

Which shows that the earthquake response of seismic-isolation structures is only 1/33 to 1/6 of that of a conventional seismic structure which means the seismic intensity is mitigated by 2.5 to 5 intensity.

- **基础隔震结构刚度与阻尼比的合理控制**
- Reasonable control of stiffness and damping ratio of base isolation

1）隔震结构的加速度反应衰减比R_a随着ω/ω_n值的增大而降低，即隔震结构的水平刚度K越小，ω_n越低，隔震效果越显著。

The attenuation ratio of seismic-isolation structures, R_a reduces with the increasing of ω/ω_n. Namely, the lower horizontal stiffness K is, the lower ω_n and the more obvious the isolation effect is.

2）隔震结构的加速度反应衰减比R_a随着隔震结构阻尼比ζ的增大而增大，即隔震结构阻尼比ζ太大，对隔震效果反而不利。

The attenuation ratio R_a increases with the damping ratio ζ. Namely, if ζ is too large, the effect of isolation is hampered.

$$R_d=\frac{D_s}{D_g}=\frac{\omega^2}{\omega_n^2}\sqrt{\frac{1}{[1-(\omega/\omega_n)^2]^2+(2\zeta\omega/\omega_n)^2}}\qquad R_a=\frac{\ddot{x}_s}{\ddot{x}_g}=\sqrt{\frac{1+(2\zeta\omega/\omega_n)^2}{[1-(\omega/\omega_n)^2]^2+(2\zeta\omega/\omega_n)^2}}$$

- **基础隔震结构刚度与阻尼比的合理控制**
- Reasonable control of stiffness and damping ratio base of base isolation

3）隔震结构的位移反应放大比R_d随着阻尼比ξ的增大而降低，即提高隔震结构的阻尼比ξ，能有效的减少隔震体系上部结构与基础间的相对位移，即有效地减少隔震装置的水平剪切变位值。

3) The displacement magnification factor(DMF) R_d decreases with increasing damping ratio ζ. That is, by increasing the damping ratio, the relative displacement of the superstructure and the base can be effectively reduced and the horizontal shear strain of seismic-isolation devices be restricted.

4）综上所述，合理选取隔震结构的刚度和阻尼，即合理选取隔震装置的水平剪切刚度K和阻尼比ζ，是对隔震结构进行合理减震控制的关键。

4) In summary, the reasonable selecting stiffness and damping for seismic-isolation structures, that is , correctly choosing the horizontal stiffness K and damping ratio ζ is the key to vibration control of seismic-isolation structures

$$R_d = \frac{D_s}{D_g} = \frac{\omega^2}{\omega_n^2}\sqrt{\frac{1}{[1-(\omega/\omega_n)^2]^2 + (2\zeta\omega/\omega_n)^2}} \qquad R_a = \frac{\ddot{x}_s}{\ddot{x}_g} = \sqrt{\frac{1+(2\zeta\omega/\omega_n)^2}{[1-(\omega/\omega_n)^2]^2 + (2\zeta\omega/\omega_n)^2}}$$

5）夹层橡胶垫的水平剪切刚度K和阻尼比ζ的选取的合理范围如下：

Reasonable scope of horizontal stiffness K and damping ζof laminated rubber bearing

$\omega/\omega_n = 2 \sim 4.5$

$\zeta = 0.10 \sim 0.30$

6）如果要控制隔震结构的加速度反应衰减比R_a为：

If given the general scope of the attenuation ratio:

$$R_a = \frac{x_s}{x_g} = 0.08 \sim 0.22$$

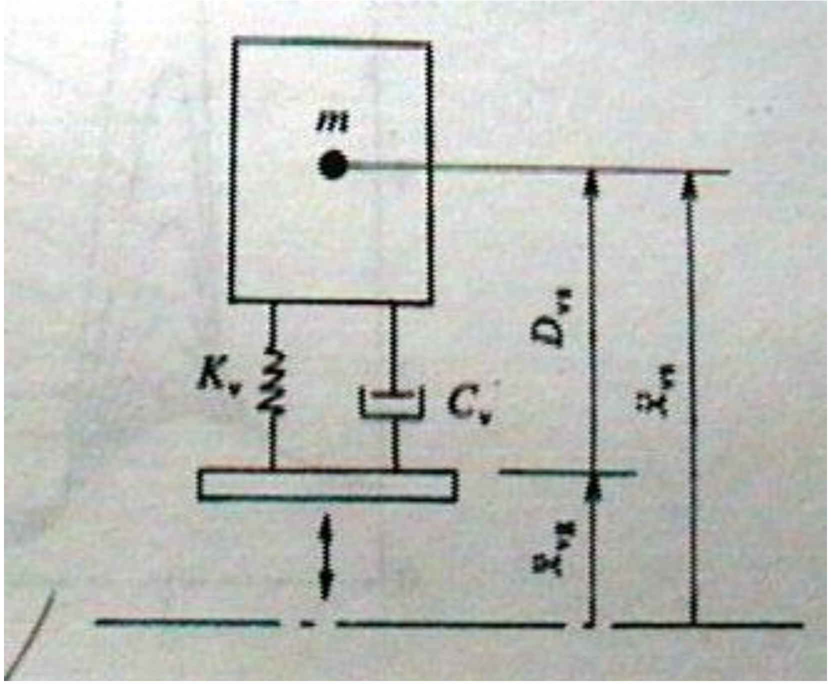
隔震结构的地震反应 $\ddot{x}_{s(g)}$ 与传统抗震结构的地震反应 $\ddot{x}_{s(c)}$ 之比为：

the ratio of acceleration response of isolation structure and conventional structure is:

$$\ddot{x}_{s(g)} / \ddot{x}_{s(c)} = 0.04 \sim 0.11 = 1/25 \sim 1/9$$

- **基础隔震体系对地面竖向震动的反应分析**

  dynamic response of base isolation system under vertical ground motion



Dynamic model:

2.4 隔震结构抗震设计

Design of seismic isolation structures

2.4.1 隔震结构的设计要求(Design requirements)

隔震结构方案的选择 Selection of seismic isolation scheme

（1）不隔震时，结构基本周期小于1.0s的多层砌体房屋、钢筋混凝土框架房屋等;

Multistory masonry or reinforced concrete frame Buildings with fundamental period of the structure less than 1 second when they are not isolated.

（2）体型基本规则，且抗震设计可用底部剪力法的房屋;

for the structures with relevant regularity, the base-shear method can be used.

（3）建筑场地宜为Ⅰ、Ⅱ、Ⅲ类，应选用稳定性较好的基础类型。

The building shall be assigned to Site-class I, II, or III; and the stable foundation types should also be selected

（4）风荷载和其他非地震作用的水平荷载不宜超过结构总重力的10%；
The total horizontal force caused by wind and other non-seismic action shall not exceed 10% of the total structural gravity

（5）隔震层应提供必要的竖向承载力、侧向刚度和阻尼；穿过隔震层的设备配管、配线，应采用柔性连接或其他有效措施以适应隔震层的罕遇地震水平位移。

The seismic-isolated layer shall provide necessary load bearing capacity, lateral stiffness and damping; the pipelines and circuits of equipments crossing the seismic-isolation story should adopt flexible connection and other effective measures to withstand the horizontal displacement during rare earthquakes

隔震建筑方案的采用，应根据建筑抗震设防类别、设防烈度、场地条件、建筑结构方案和建筑使用要求，与采用抗震设计的方案进行技术、经济可行性综合比较分析后确定。

The design of seismic-isolated building structures should be determined after the technical and economic feasibility comparison analysis, which should be given consideration to fortification category, the fortification intensity, the conditions of sites, building structural plans and the use requirements.

- 隔震层的设置 setup of seismic-isolation story

隔震层的布置应符合以下要求：the setup of seismic-isolation story should meet following requirements

（1）隔震层可由隔震支座、阻尼装置和抗风装置组成，阻尼装置和抗风装置可与隔震支座合为一体，亦可单独设置。必要时可设置限位装置。

The seismic isolation layer can consist of isolators, damping device and wind resistant device. Damping device and wind resistant can be used together with Isolation bearings, or be set separately. Displacement limitation device can also be set if necessary.

（2）隔震层刚度中心宜与上部结构的质量中心重合。

The center of stiffness of the isolation layer should coincide with the center of mass of the superstructure

（3）隔震支座的平面布置宜与上部结构和下部结构的竖向受力构件的平面位置相对应。

The layout of isolation bearings should correspond with that of the vertical bearing components of the superstructure and substructure

（4）同一房屋选用多种规格的隔震支座时，应注意充分发挥每个隔震支座的承载力和水平变形能力。

When using different types of isolation bearings in a building, the bearing capacity and capacity of lateral deformation should be utilized

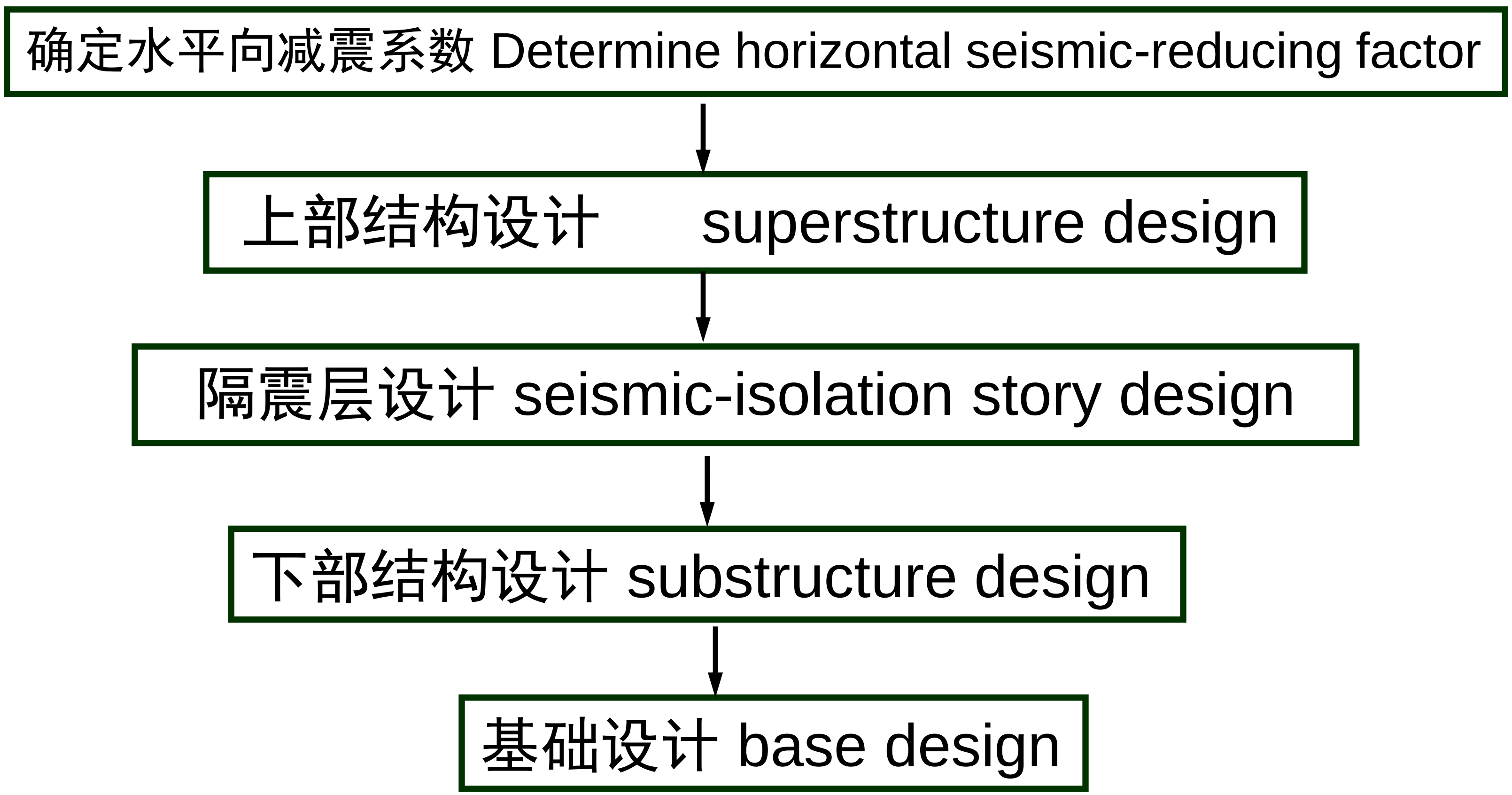
（5）同一支承处选用多个隔震支座时，隔震支座之间的净距应大于安装操作所需要的空间要求。

When multiple bearings are used on the same support, the spacing between the isolation bearing should be larger enough to install them.

（6）设置在隔震层的抗风装置宜对称、分散地布置在建筑物的周边或周边附近。

The wind resistant devices on the isolation layer should be layout symmetrically and dispersedly around the building

2.4.2 隔震结构的抗震设计—分步设计法
Design of seismic isolation structures—Step-by-step method



隔震设计的基本步骤 processing of seismic isolation design

- Requirements of calculation analysis of seismic isolation structures

（1）隔震体系的计算简图可采用剪切型结构模型；当上部结构的质心与隔震层刚度中心不重合时应计入扭转变形的影响。隔震层顶部的梁板结构，对钢筋混凝土结构应作为其上部结构的一部分进行计算和设计。

The calculation model of the seismic-isolation building structures may adopt the shear type model. When the gravity center of the structure above the isolation story and the rigidity center of the isolation story are not in a line, he influence of torsion deformation shall be taken into consideration. For the reinforced concrete seismic-isolated structures, the beam-slab structures above the isolation interface shall be deemed as a part of the structure above the isolation story for calculation and design.

（2）一般情况下，宜采用时程分析法进行计算；输入地震波的反应谱特性和数量，应符合《抗震规范》的规定；计算结果宜取其平均值；当处于发震断层10km以内时，若输入地震波未计及近场影响，对甲、乙类建筑，计算结果尚应乘以下列近场影响系数：5km以内取1.5，5km以外取1.25。

In generally, the calculation should adopt the time-history analyzing method; the response spectrum characteristics and amount of the input seismic wave shall comply with the provisions in the Seismic Code ; the calculation result should choose the average value. When building assigned to category A and B is located within 10km of the causative fault and the input seismic-wave is not the near-field accelerogram, the calculation results shall be multiplied by the following near-field affected factors: within 5km, multiplied by1.5; beyond 5km, multiplied by 1.25.

（3）砌体结构及基本周期与其相当的结构可按底部剪力法简化计算。对水平向减震系数及隔震后体系的基本周期按相关计算公式确定。

Masonry structures and structures similar to its fundamental period may carry out simplified calculation provided according to the base shear method.
The horizontal seismic-reducing factor and the fundamental period can be determined according to the relevant calculation fomular.

- 水平向减震系数 Horizontal seismic-reduced factor

叠层橡胶隔震支座只具有隔离或耗散水平地震的功能，对竖向地震隔震效果不明显，为了反应隔震建筑隔震层以上结构水平地震反应减小这一情况，引入“水平向减震系数”。由于隔震层对竖向隔震效果不明显，故当设防烈度为9度和8度且水平向减震系数为0. 25时，隔震层以上的结构应进行竖向地震作用的计算；当设防烈度为8度且水平向减震系数小于0. 5时，宜进行竖向地震作用的计算。

Laminated rubber bearings only have the function of isolating or dissipating horizontal earthquake effect and they are weak to isolate vertical earthquake effect. In order to reflect the reduction of the horizontal seismic response of the structures above the seismic-isolated story, the horizontal seismic-reduced factor is introduced. he calculation of the vertical seismic action for structures above the seismic-isolation story shall be carried out for Intensity 9 or for Intensity 8'with the horizontal seismic-reduced factor 0.25. And the calculation for vertical seismic action should be carried out for Intensity 8 with the seismic-reduced factor not greater than 0.5.

- 水平向减震系数 horizontal seismic-reduced factor

表1 层间剪力最大比值与水平向减震系数的对应关系

Table 1 Corresponding relation of the maximum ratio of story shear force and the horizontal seismic-reduced factor

层间剪力比值 Max. ratio of story shear force	**0.53**	**0.35**	**0.26**	**0.18**
水平向减震系数 Horizontal seismic-reduced factor	**0.75**	**0.50**	**0.38**	**0.25**

- 隔震层的设计 Design of seismic-isolation story
  - 隔震层的设置要求 Installment requirements of seismic-isolation story

隔震层宜设置在结构第一层以下的部位，其橡胶隔震支座应设置在受力较大的位置，间距不宜过大，其规格、数量和分布应根据竖向承载力、侧向刚度和阻尼的要求通过计算确定。隔震层在罕遇地震下应保持稳定，不宜出现不可恢复的变形。隔震层橡胶支座在罕遇地震作用下，不宜出现拉应力。

The seismic-isolation story should be installed at locations under the first story of the structure. The rubber isolator units shall be placed at locations where the interior forces are greater, the spacing should not be too large; the size, amount and distribution shall be determined according to the requirements of the vertical bearing capacity, the lateral stiffness and the damping. The seismic-isolation story shall be stabilized under rare earthquake, and should not have non-restorable deformations. The rubber isolator units should not have tensile stress under the rare earthquakes.

- 隔震层的设计 Design of seismic-isolation story

- 水平动刚度和等效粘滞阻尼比的计算

The horizontal dynamic stiffness and equivalent viscous damping ratio can be calculated according to the following equations:

$$K_h = \sum K_j \qquad \zeta_{eq} = \sum K_j \zeta_j / K_h$$

- 橡胶隔震垫的水平刚度和阻尼比的试验确定

The determination by testing of the horizontal stiffness and damping ratio of the laminated rubber bearing

隔震支座由试验确定设计参数时，竖向荷载应保持《规范》的平均压应力限值。对多遇地震验算，宜采用水平加载频率为0. 3HZ且隔震支座剪切变形为50%的水平刚度和等效粘滞阻尼比；

When the design parameters of the isolator units are determined by testing, the vertical load shall keep the limit values of average compressive stress of provision in the seismic code. For checking of frequent earthquakes, the horizontal stiffness and equivalent viscous damping ratio shall be determined by test where horizontal loading frequency is 0.31Hz and the shear deformation of the unit is 50 % .

- 橡胶隔震垫的水平刚度和阻尼比的试验确定

The determination by testing of the horizontal stiffness and damping ratio of the laminated rubber bearing

对罕遇地震验算，直径小于600mm的隔震支座宜采用水平加载频率为0.1HZ且隔震支座剪切变形不小于250%时的水平动刚度和等效粘滞阻尼比；直径不小于600mm的隔震支座可采用水平加载频率为0.2HZ且隔震支座剪切变形为100%时的水平刚度和等效粘滞阻尼比。

For checking of rare earthquake and the isolator units with a diameter smaller than 600mm, the horizontal stiffness and equivalent viscous damping ratio should be determined by test where horizontal loading frequency is 0. 1Hz and the shear deformation of the unit is 250% .For checking of rare earthquake and the isolator units with a diameter not smaller than 600mm , the horizontal stiffness and equivalent viscous damping ratio may be determined by test where horizontal loading frequency is 0.2Hz and the shear deformation of the unit is 100 %

橡胶隔震支座平均压应力限值和拉应力规定

Limit values of the average compressive for rubber isolator unit and the regulations on the tensile stress

橡胶支座的压应力即是确保橡胶隔震支座在无地震时正常使用的重要指标，也是直接影响橡胶隔震支座在地震作用时其他各种力学性能的重要指标。它是设计或选用隔震支座的关键因素之一。在永久荷载和可变荷载作用下组合的竖向平均压应力设计值不应超过下表的规定，在罕遇地震作用下，不宜出现拉应力。

The compressive stress of the Rubber bearings is the important indicator to ensure that the rubber bearings works properly without earthquake. And it is also an indicator to directly influence the various mechanical properties of rubber bearings under earthquake effect. It is one of the key factors to choose and design the rubber. Under the combination of permanent loads and variable loads, The design values of average vertical compressive stress should not exceed the limitations in the table. And tensile stress should not occur in rare earthquake

橡胶隔震支座平均压应力限值

Limit values of the average compressive for rubber isolator unit

建筑类别	甲类建筑	乙类建筑	丙类建筑
平均压应力 /MPa	10	12	15

- 隔震支座的水平剪力

Horizontal shear force of the isolator unit

隔震支座的水平剪力应根据隔震层在罕遇地震作用下的水平剪力按各隔震支座的水平刚度分配。当考虑扭转时，尚应计入隔震支座的扭转刚度。

隔震层在罕遇地震下的水平剪力宜采用时程分析法计算。

The shear force of the isolator unit shall be determined according to the horizontal stiffness of all isolator units from which is the horizontal shear force of the seismic-isolation story under the rare earthquake. When calculation considered torsion, the torsion stiffness of the isolator unit shall be taken into consideration.

The calculation of the shear force of the seismic-isolated story in rare earthquake should adopt the time-history analyzing method

隔震支座在罕遇地震作用下的水平位移验算

The horizontal displacement of the isolator unit under rare earthquake

$$u_i \le [u_i] \qquad u_i = \beta_i u_c$$

u_i—罕遇地震下，第*i*个隔震支座考虑扭转的水平位移(Horizontal displacement of *i-th* isolator unit when taking into account of the torsion under the rare earthquakes).

$[u_i]$—第*i*个隔震支座的水平位移限值，对橡胶隔震支座，不宜超过该支座橡胶直径的0.55倍和支座橡胶总厚度3.0倍二者的较小者；(Limit value of horizontal displacement of i-th isolator unit; in the case of rubber isolator unit, its displacement shall not exceed 0.55 times of the effective diameter of the unit or 3 times of the total thickness of all rubber layers, whichever is smaller.)

u_c—罕遇地震下隔震层质心处或不考虑扭转的水平位移;(Horizontal displacement in the center of the seismic-isolation story under rare earthquakes, or when torsion is not taken into consideration.)

β_i—隔震层扭转影响系数(Torsion factor of i-th seismic-isolator unit)

- 上部结构的抗震计算

  Seismic calculation of the superstructure

- Calculating the total horizontal seismic action by base-shear method
- calculating the seismic action of the superstructure: equal to the product of total horizontal seismic action and horizontal seismic-reduced factor provided by tab. 1
- distribution of the horizontal seismic action of superstructure may adopt rectangular
- The calculation of the vertical seismic action is the same as non-seismic-isolated structure

- 隔震层以下结构计算 Calculation of the structures under the seismic-isolation story

隔震层以下结构（包括地下室）的地震作用和抗震验算，应采用罕遇地震下隔震支座底部的竖向力、水平力和力矩进行计算。

The seismic action and check for structures under the seismic-isolation story shall adopt the vertical force, horizontal force and moment of force at the bottom of the isolator units under rare earthquake.

2. 4. 5 隔震结构的构造措施
Details of seismic-isolated structures

- 上部结构的构造要求 details for superstructure

（1）隔震层以上结构应采取不阻碍隔震层在罕遇地震下发生大变形的下列措施：

For structural systems above the seismic-isolation story, the following details, which will not disturb significant displacement of the seismic-isolation story under rare earthquake, shall be taken:

①上部结构的周边应设置防震缝，缝宽不宜小于各隔震支座在罕遇地震下的最大位移值的1.2倍。

The seismic joints shall be installed along the perimeter of the structure above the seismic-isolation story, the width of the joint should not be less than 1.2 times of the maximum horizontal displacement of each seismic-isolator unit under the rare earthquake;

- 上部结构的构造要求 details for superstructure

②上部结构（包括与其相连的任何构件）与地面（包括地下室与其相连的构件）之间，宜设置明确的水平隔震缝；当设置水平隔震缝确有困难时，应设置可靠的水平滑移垫层。

Between the structure (including connected members) above the seismic-isolation story and the ground surface (including foundation and structures below the isolation interface)，the clear horizontal separations shall be installed; when it is difficult to install horizontal separations, a reliable horizontal slipped cushion shall be installed;

③在走廊、楼梯、电梯等部位，应无任何障碍物。

In location such as the corridors, the staircase, and the elevators etc.，shall be no any obstruction for movement.

- 上部结构的构造要求 details for superstructure

（2）丙类建筑在隔震层以上的结构抗震措施：当水平向减震系数为0. 75时不应降低非隔震时的有关要求；水平向减震系数不大于0. 50时，可适当降低非隔震建筑的要求，但与抵抗竖向地震作用有关的抗震构造措施不应降低。

For the buildings assigned to Category C, the seismic-measures of structures above the seismic-isolation story shall not reduce the requirements in non-isolated provision of this code when the horizontal seismic-reduced factor is 0.75. And the requirements in non-isolated provisions may be properly loosened when this factor is not greater than 0.5 , but corresponding vertical seismic detail requirements shall not be loosened.

●隔震层顶部梁板体系的构造要求

Details of isolation layer on top of the beam-slab system

为了保证隔震层能够整体协调工作，隔震层顶部应设置平面刚度足够大的梁板体系。为保证隔震层顶部梁板的刚度和承载力大于一般楼面的刚度和承载力，需增大梁板的平面内刚度，加大梁截面尺寸和配筋，上部结构为砌体时，其构造应符合有关底部框架砖房的钢筋混凝土托梁的要求；上部结构为框架等钢筋混凝土结构时，其构造宜符合关于框支层的有关要求。

隔震支座附近的梁柱受力状态复杂，地震时还会受冲切，因此，应考虑冲切和局部承压，加密箍筋并根据需要配置网状钢筋。

In order to ensure the overall coordination of the isolation layer, a beam-slab system with sufficient stiffness should be set on the top of the seismic-isolation story. To ensure the stiffness and bearing capacity of the beam and the slab on the top of the seismic-isolation story are greater than those of an ordinary floor, the in-plane stiffness of the slab and beam must be increase and so do the reinforcement and cross-sectional dimensions of the beams.

The beams and columns near the isolation bearings are under complex stress, which even includes punching in earthquake. Thus, with punching and local compression taken into consideration, we should should increase the stirrups and set steel meshs.

●隔震层的构造要求 Details for seismic-isolation story

隔震层应由隔震支座、阻尼器和为地基微震动与风荷载提供初刚度的部件组成，阻尼器可与隔震支座成为一体，亦可单独设计。必要时，宜设置防风锁定装置。

The seismic-isolation story consists of isolation bearings, dampers and components with the primary stiffness to resist the pulsation of the ground and the wind load. The dampers and bearing can be designed together or separately, and, if necessary wind lock devices should be set

（1）多层砌体房屋的隔震层位于地下室顶部时，隔震支座不宜直接放置在砌体墙上，并应验算砌体的局部承压；

When the seismic-isolation story of multi-story masonry building locates at the top of the basement, the isolator-unit should not be placed on the masonry wall directly, and the local compressive capacity of the masonry wall shall be checked too.

●隔震层的构造要求 Details of seismic-isolation story

（2）隔震支座和阻尼器应安装在便于维护人员接近的部位。The isolator units and the damper shall be installed in locations where the maintenance personnel can access easily

（3）隔震支座与上部结构、基础结构之间的连接件，应能传递支座的最大水平剪力。

The connected elements of the isolator unit with the floor of the top of the seisimc-isolation story and with the foundation shall be able to transfer the maximum horizontal shear force of the isolator unit under rare earthquake.

●隔震层的构造要求
Details of seismic-isolation story

（4）外露的预埋件应有可靠的防锈措施。预埋件的锚固钢筋应与钢板牢固连接，锚固钢筋的锚固长度应大于20倍锚固钢筋直径，且不应小于250㎜。隔震支座连接定位时，支座底部的中心，标高偏差不大于5㎜，平面位置的偏差不大于3㎜。 单个支座的倾斜度不大于1/300。

Exposed embedded parts shall have reliable anti-rust treatment. The anchoring reinforcements of the embedded parts shall be connected to the steel plate firmly，the developed length of the anchoring reinforcement should be greater than 20 times of diameter of the anchoring bar or 250mm, whichever is greater.

（5）隔震墙下隔震支座的间距不宜大于2.0m。

The spacing of the isolator units under the wall shall not be greater than 2.0m