我国城镇与重大工程抗震防灾研究若干进展与挑战

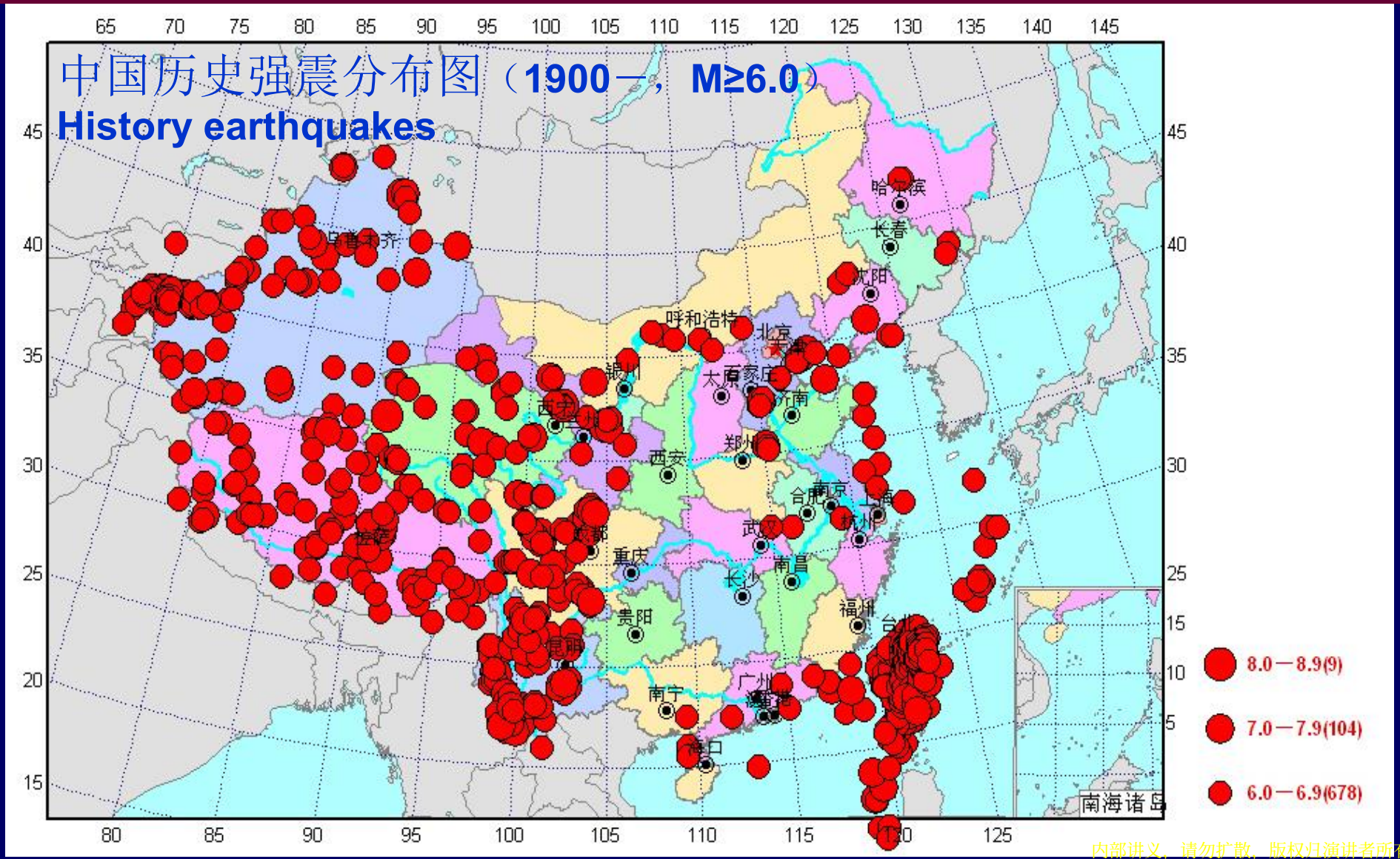
欧进萍 Jinping Ou

HIT and DUT, China

2018. 04. 23

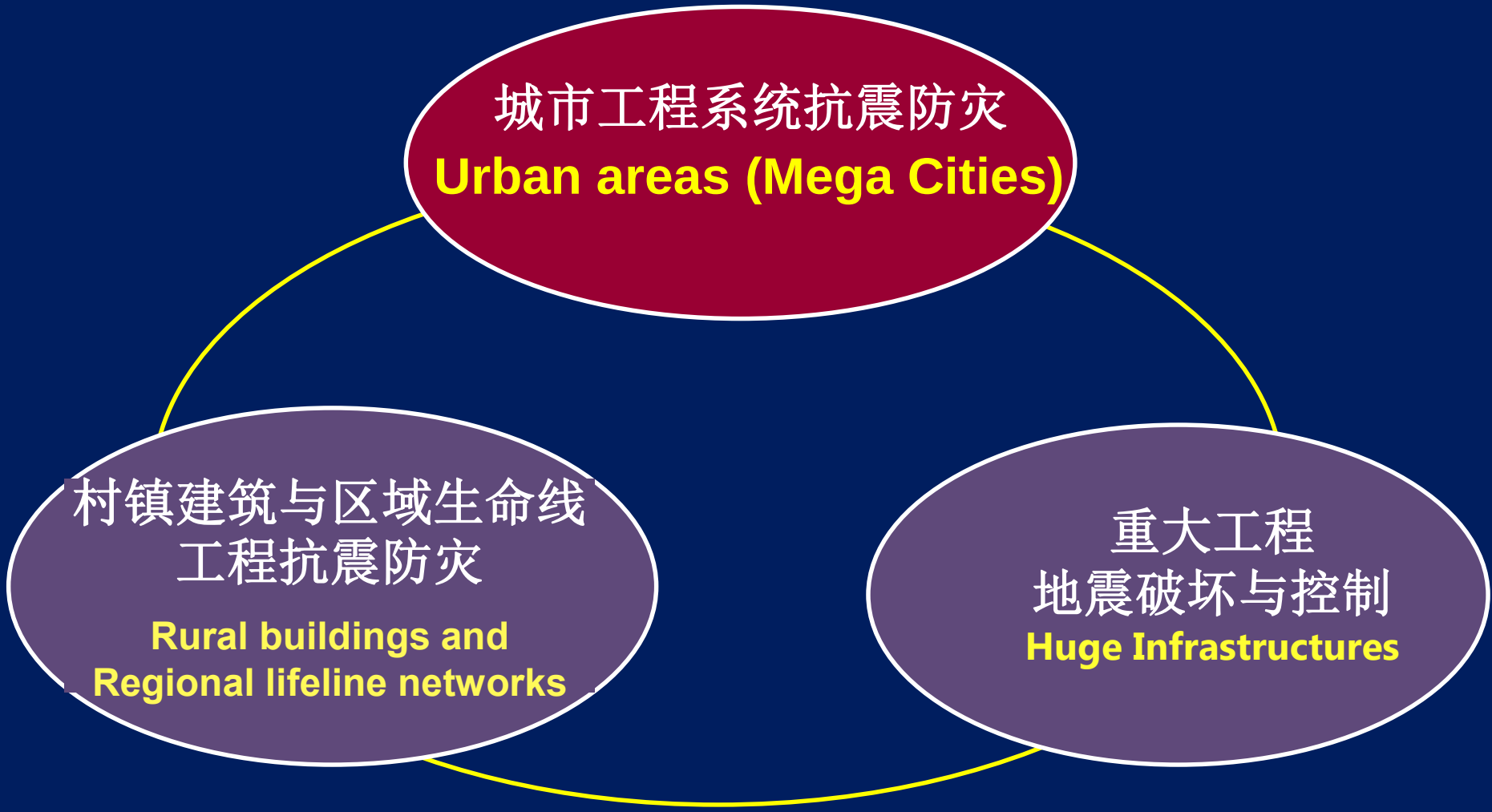
内部讲义，请勿扩散，版权归演讲者所有

Earthquakes often occur in mainland China, some of which can be very strong, such as Tangshan (1976) and Wenchuan (2008) earthquakes



内部讲义，请勿扩散，版权归演讲者所有

中国工程抗震的三大领域
Main Issues of Earthquake Engineering in China



内部讲义，请勿扩散，版权归演讲者所有

I. Lessons from Wenchuan Earthquake Disaster and Rural Earthquake Disater Prevention in China

汶川地震灾害教训与村镇区域地震防御

内部讲义，请勿扩散，版权归演讲者所有

●2008 Wenchuan Earthquake (M8.0)

(14:28, 2008.5.12, Sichuan Province)

About 70,000 dead, economic lost ￥800B ($130B)

2008汶川地震(**8.0**级): 约**7**万人死亡、损失超过**8000**亿人民币

● **2010 Yushu Earthquake(M7.1)**

(07:49, 2010.4.14, Qinghai Province)

About 2,700 dead

2010玉树地震(**7.1**级): 约**2,700**死亡

● **2013 Lushan Earthquake(M7.1)**

(08:02, 2013.4.20, Qinghai Province)

About 170 dead, economic lost ￥65.5B($10B)

2013卢山地震（**7.1**级）: 约**170**人死亡，、损失超过**655**亿人民币

● **2014 Ludian Earthquake(M6.5)**

(16:30, 2014.8.3, Yunnan Province)

617 dead

2014鲁甸地震(**6.5**级): **617**死亡

● **2014 Yongshan Earthquake(M5.0)**

(06:07, 2014.8.17, Yunnan Province)

2014永善地震（**5.0**级）

……

内部讲义，请勿扩散，版权归演讲者所有

Disaster Comparisons in Wenchuan, Chile and Haiti Earthquakes

汶川、智利和海地地震的震害比较

Place 地点	Wenchuan 汶川	Chile 智利	Haiti 海地
Time 时间	2008.5.12	2010.2.27	2010.1.12
Magnitude 震级	8.0	8.8	7.7
Hypocenter Depth 震源深度	14km	59.4km	10km
People Dead 死亡人数	6,9227	507	22,2500

Why? Aseismic capacity of buildings !

Rural earthquake prevention in China faces challenges, may from S&T, economics and construction administration !

中国村镇地震防御面临巨大的挑战

——有科技、经济和建设管理等方面的问题！

内部讲义，请勿扩散，版权归演讲者所有

Major consultant project supported by
China Academy of Engineering
中国工程院重大咨询项目

Seismic damage and strategy of Engineering in Wenchuan earthquake
汶川地震的工程破坏与对策

Planed Sum:￥5 Million

PI： Jinping Ou
项目负责人：欧进萍

Jan. 2010-Dec. 2011

内部讲义，请勿扩散，版权归演讲者所有

Objectives—项目目标

- Summarize the earthquake engineering disaster from scientific view

集成和升华汶川地震工程震害的科学认识

- Put forward suggestions on the recovery of buildings and region lifeline networks in disaster areas

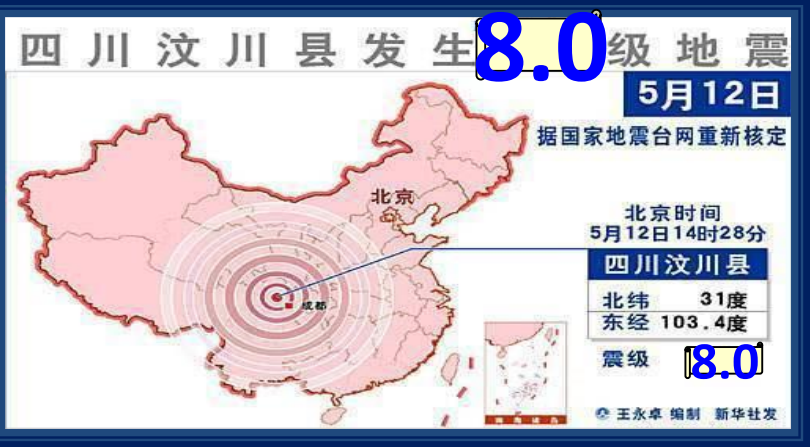
提出汶川地震恢复重建在建工程和拟建工程咨询意见

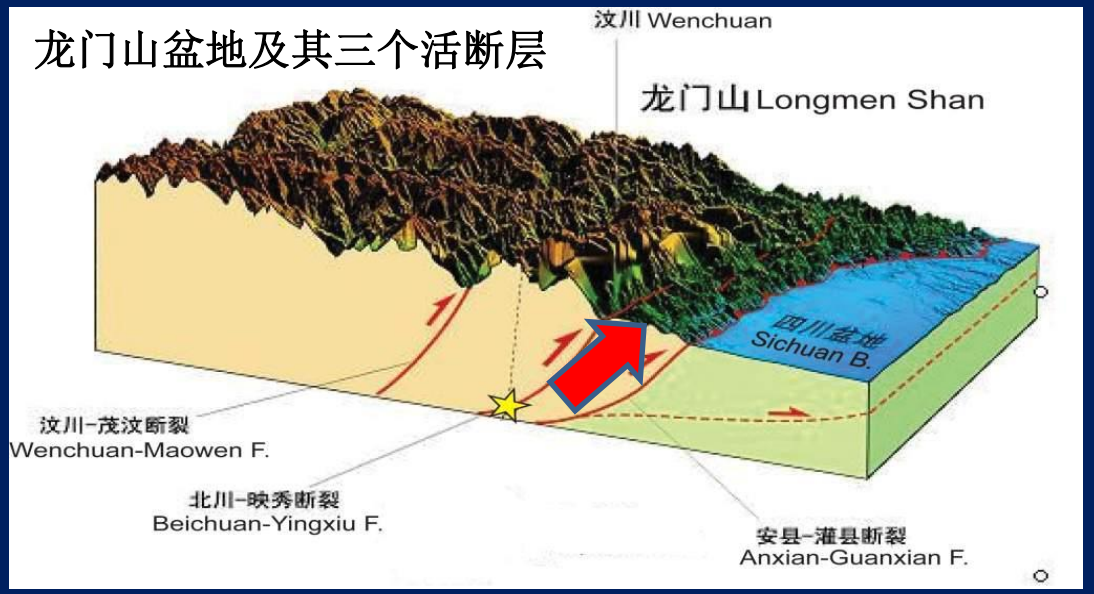
- Provide suggestions and potential paths to improve aseismic capacity of rural buildings and region lifeline networks in the whole country ,including research, technology transfer, design code, administration law and policy etc.

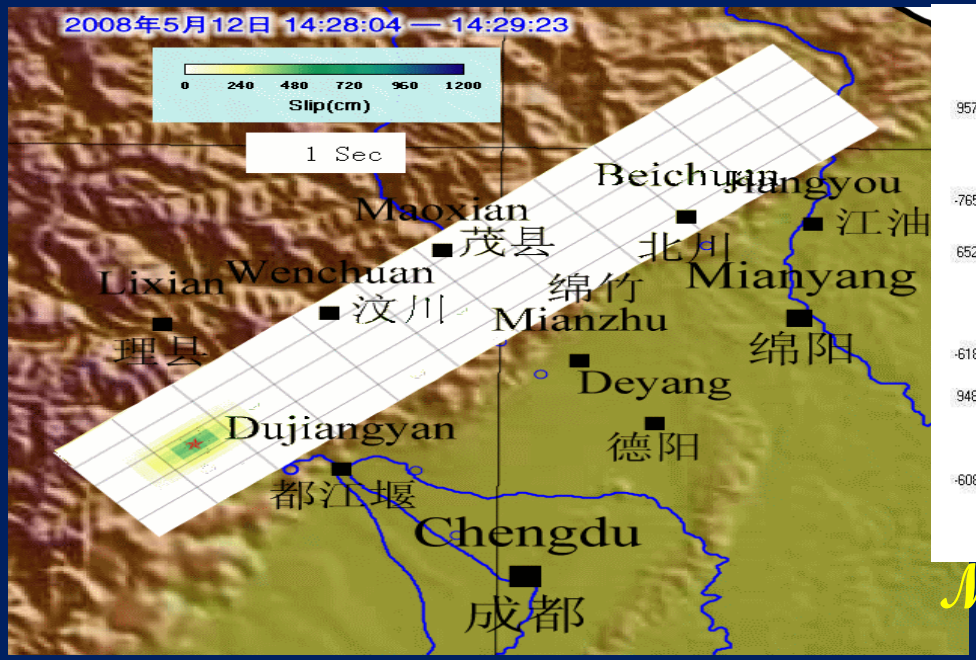
提出全国城镇区域未来抗震防灾科技研究、政策法规和工程建设对策的建议

内部讲义，请勿扩散，版权归演讲者所有

1.Strong Ground Motion
强地震动

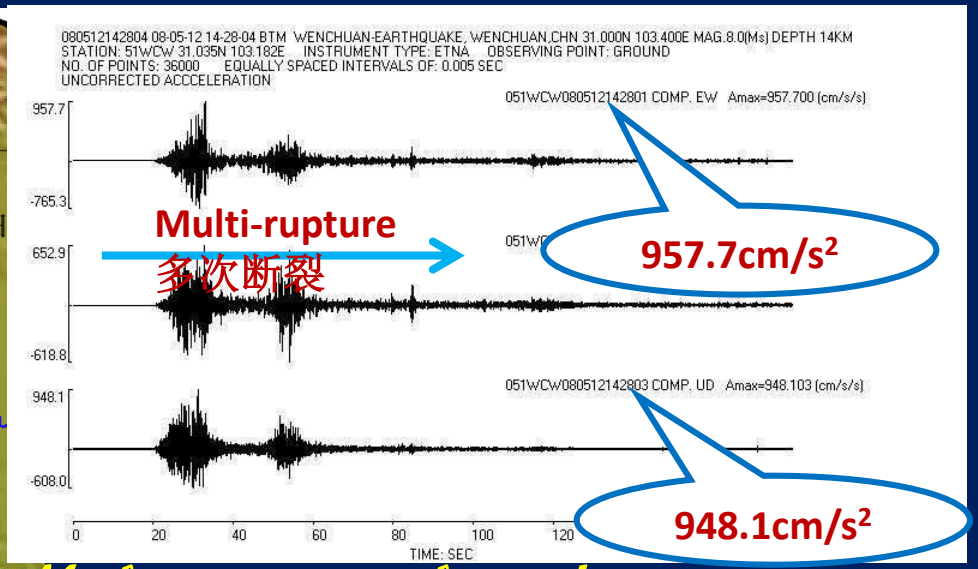






Lengths of the surface ruptures

表面破裂长度：225km,95km



Multi-ruptures, long duration, strong vertical intensity

多次破裂、长持时、大竖向加速度

距离震中22.2km、断层1.09km最大加速度记录（卧龙台）

内部讲义，请勿扩散，版权归演讲者所有

Lesson 1： The intensity and properties of earthquake possesses strong randomicity, the intensity of EQ which would occurs future may be much higher than the fortified one.

1. The EQ intensity for some important infrastructure such as school and hospital buildings and also dams should be set up a larger intensity than the fortified one.
2. Challenges in the EQ intensities zoning!

——The fourth generation of EQ zoning map have been making and almost finished in China after Wenchuan EQ.

教训1：地震强度和特性具有很强的随机性，未来发生的地震强度可能远超过设防烈度。

1. 地震区划面临很大的挑战
2. 对特别重要的工程（如学校、医院、大坝等）应考虑高于当地地震设防烈度

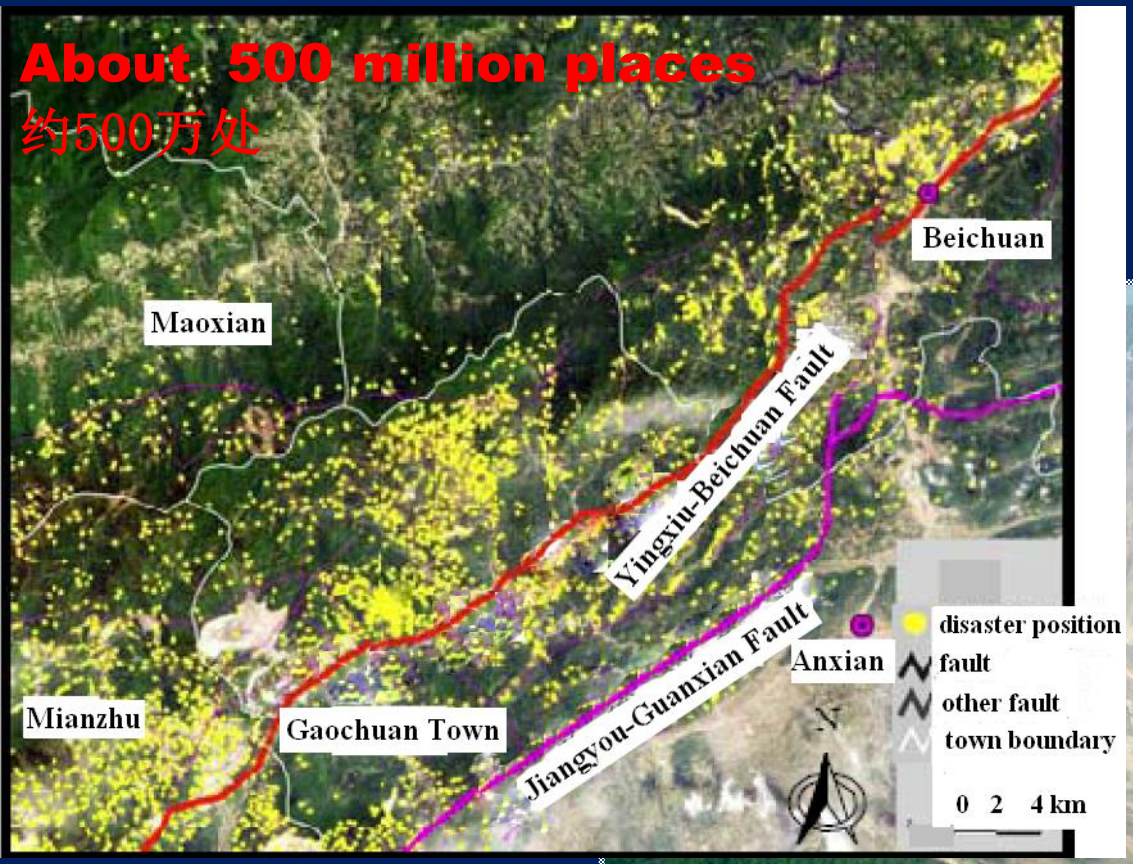
——汶川地震后，中国第四代地震区划正在加紧进行和完成

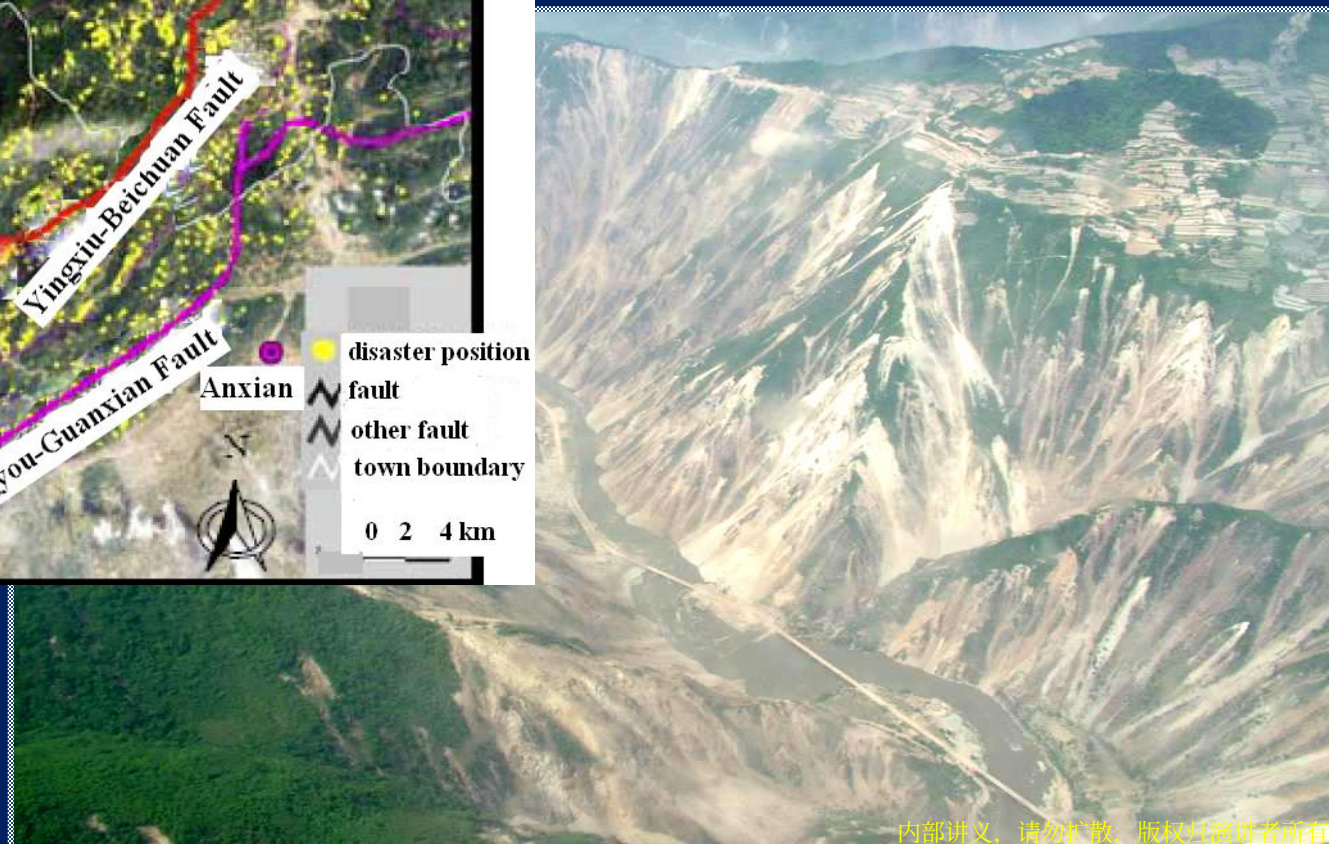
The fortified earthquake intensities in this area !
本地区的设防烈度！

Ⅷ	25380	5470
Ⅶ	52630	25030（land）
Ⅵ	231110	（about 75000）
Total area	324080	
Total area		≥Ⅴ 216000

内部讲义，请勿扩散，版权归演讲者所有

2. Widely and severe geological disaster
严重的地震地质灾害(Huang Runqiu，2008)

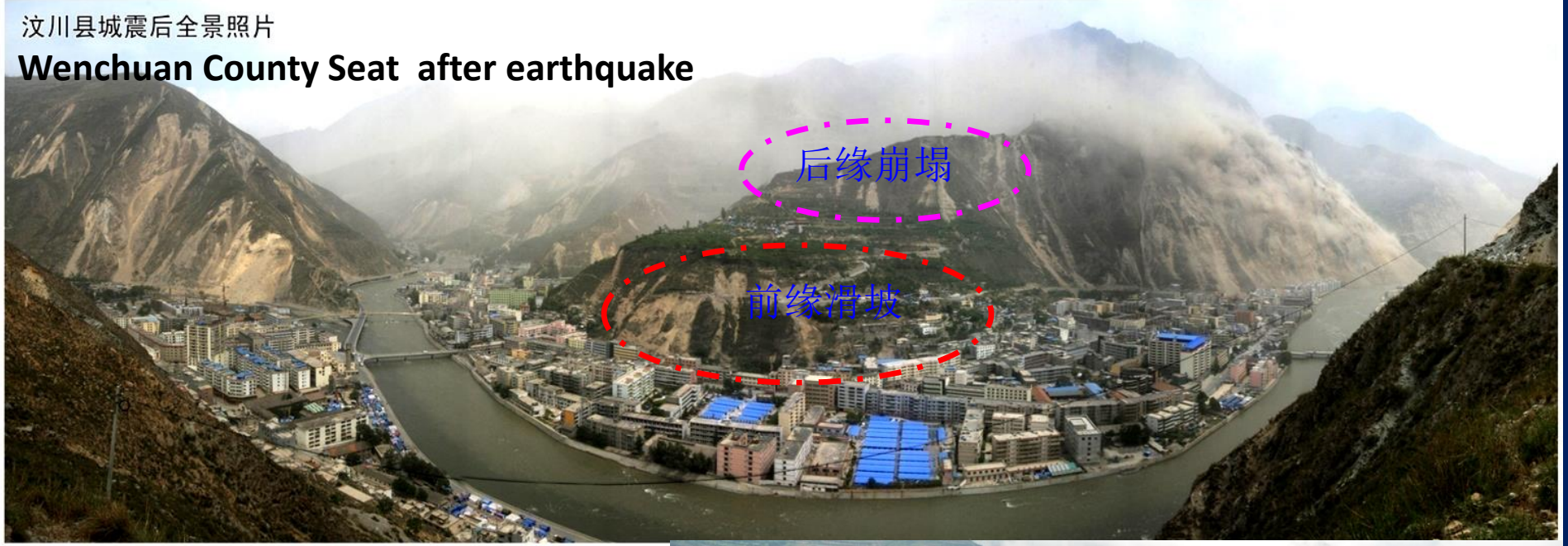




内部讲义，请勿扩散，版权归演讲者所有

汶川县城震后全景照片

Wenchuan County Seat after earthquake



The quaked-cracked mountains or hills is still stable?

How to predict and prevent ?

How to treatment the endangered towns, including selecting their new places?

震裂山体是否稳定？

如何预测和防治？

危及的城镇如何处置？

搬迁如何选址？

震裂山体质量劣化，边坡失稳方式为沿强风化卸荷带“剥皮型”滑坡或浅层崩塌、落石。

阿坝师专

内部讲义，请勿扩散，版权归演讲者所有

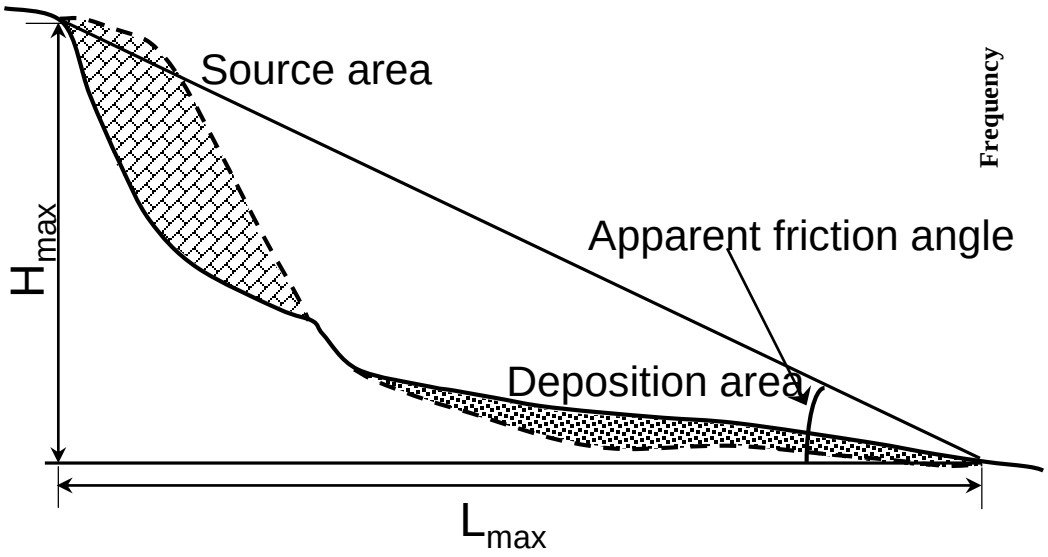
Lesson 2： In the recovery of disaster area, the distance from the landslide and rock falls must be taken into account for the new places selected for towns.

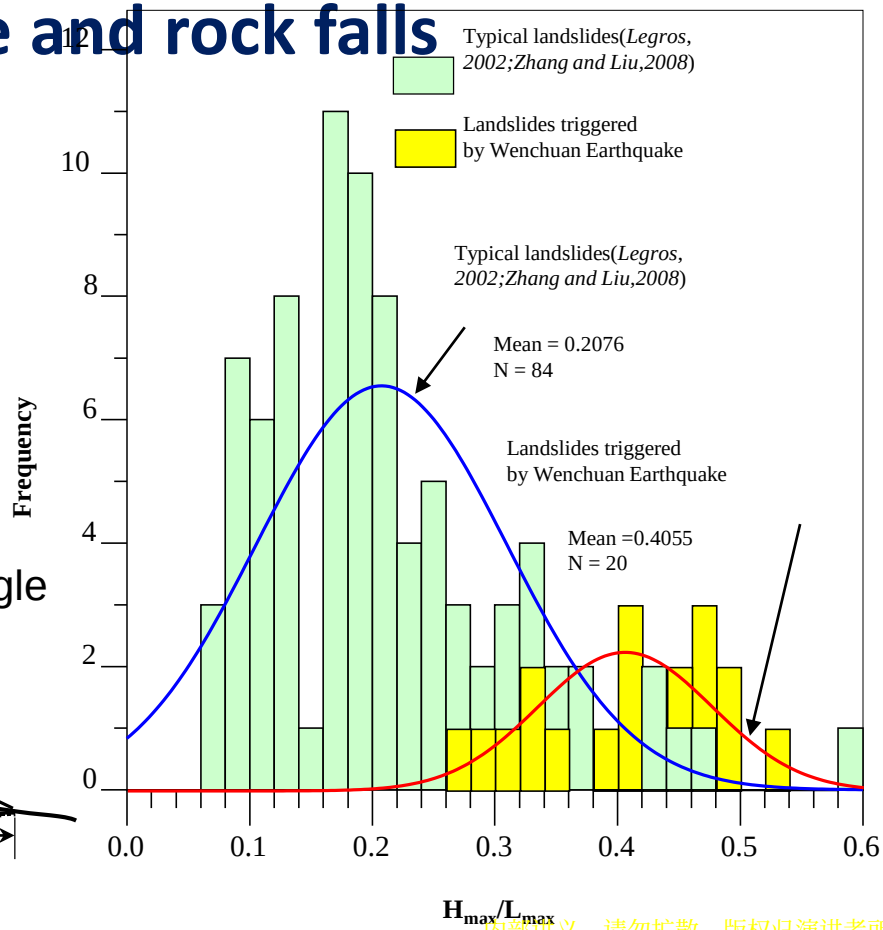
And the quake-cracked mountains or hills must be treated and monitored.

教训2：地震恢复重建时， 新的村镇选址要考虑滑坡和滚石的避让距离。震裂山体要处置和监测。

The distance from the landslide and rock falls

$$Lmax=2.5\sim3.0\ Hmax$$





内部讲义，请勿扩散，版权归演讲者所有

3. A great number of building damaged or destroyed
大量的房屋建筑破坏

Yingxiu Town: before and after the shock
震前震后的映秀

Beichuan Town: before and after the shock
震前震后的北川

A lot of school building destroyed
大量的中小学建筑倒塌
——北川中学

——汉王镇绵竹中学

Damageable rural buildings
村镇建筑“不堪一击”

Severe damaged historical buildings
文化遗产建筑破坏严重

About 6 million buildings severe damaged and 5.5million buildings collapsed, including the buildings of 13,768 schools and 10,250 hospitals.
地震共导致593.25万间房屋严重损坏，546.19万间倒塌，包括学校13,768所和10,250个医院的房屋。

About 140 historical buildings damaged or collapsed, in which the wooden structures showed better aseismic capacity than the masonry structures.
地震受损的文化遗产建筑有木结构140处、砖石结构57处、其它结构形式23处。
砖石结构文化遗产建筑抗震性能低于木结构文化遗产建筑。

内部讲义，请勿扩散，版权归演讲者所有

Lesson 3： The buildings designed strictly according to the current seismic codes were damaged lightly and few of them collapsed.

Almost all of rural buildings without seismic design in the disaster area were totally collapsed. The rural buildings must be constructed under the special administration and must be designed against earthquake.

A lot of school buildings collapsed in the disaster area made many pupils dead and very bad social impact. The aseismic capacity of school buildings have to be enhanced to higher level than common buildings.

教训3：按规范抗震设计的建筑损伤较轻、倒塌较少、具有较好的抗震能力。

地震区的农房几乎全部倒塌，农村房屋没有设计和建设没有监管的状况必须改变。

大量的中小学建筑倒塌致使不少学生死亡和造成极坏的社会影响。中小

After Wenchuan earthquake, all of school buildings in China have to be made for seismic safety evaluation and retrofit under the requirement of the central government since 2008

2008汶川地震后，中国政府要求所有的中小学建筑要进行抗震安全评定和加固！

内部讲义，请勿扩散，版权归演讲者所有

4. Collapse of bridges and destruction of road networks

桥梁崩塌、公路网络破坏

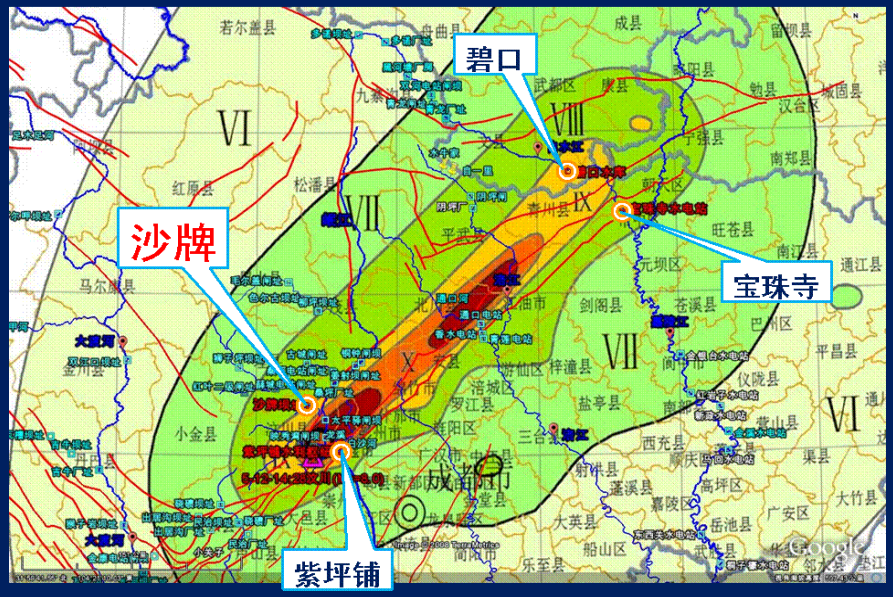
34,125 km road was damaged and interrupted, in which 1,109 bridges were damaged or collapsed and 52 tunnels were damaged or destroyed.

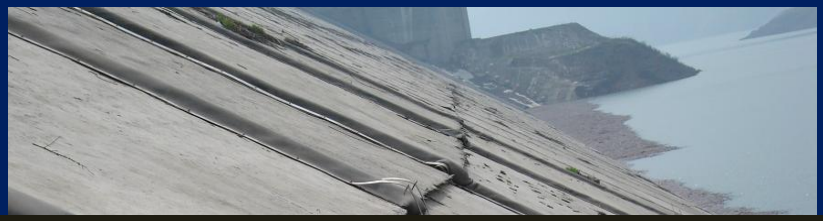
地震受损公路总里程达34,125km，直接经济损失612亿元，其中高速公路和国省干线公路受损桥梁1,109座共8.2万延米，隧道52座共4.7万延米。

内部讲义，请勿扩散，版权归演讲者所有

5. Aseismic safety impact and verification of dams

大坝地震安全受到威胁





All of the dams were not collapsed and showed the good aseismic capacity since the dams were designed under higher earthquake intensity strictly according to Chinese codes.

所有大坝没有溃坝、表现出了良好的抗震性能，其中重要的一个原因是大坝按较高的设防地震烈度、严格按照规范进行了抗震设计。

内部讲义，请勿扩散，版权归演讲者所有

7. Main advances of permanent settlement & recovery after earthquake

A successful proposal and experience: Aided and donated by other provinces

震后安置与恢复重建进展　一个成功的做法：“对口支援”

7.1 New place selection and planning of towns 村镇选址与规划

The distance far from the active faults and possible landsides was taken into account at a certain extent.

活断层避让距离和潜在滑坡避让距离得到一定程度的考虑和采纳

Yingxiu Town newly planned

内部讲义，请勿扩散，版权归演讲者所有

7.2 School buildings： designed and constructed firstly, completed before Sept.1, 2009

A program and action in whole country: Safety evaluation and Retrofit for all of school building

学校建筑：首先设计建设、2009年9月1日全部完成

推动了全国中小学建筑普查、抗震加固

Primary and middle school buildings donated by Shanghai in Dujiangyan

上海市老干部捐助修建的都江堰北街小学和中学

内部讲义，请勿扩散，版权归演讲者所有

7.3 Rural buildings： designed and constructed with seismic consideration

There is a long way for seismic design and construction administration in the whole country!

农村建筑设计和建设一定程度上考虑了抗震的要求，但全中国的农村建筑建设监管和抗震设计任重道远！

Rural buildings with Tibet feature
具有藏族风格的村镇民居

Rural buildings (RC and steel frame structures, 3 story house/family
钢筋混凝土和钢结构框架村镇建筑/一户三层）

内部讲义，请勿扩散，版权归演讲者所有

7.4 A number of new infrastructures rebuilt
基础设施得到极大改善

- It takes 1 hour from Dujiangyan to Wenchuan before earthquake
- New highway to shorten the time from 1 hour to 10 min after earthquake

内部讲义，请勿扩散，版权归演讲者所有

7.5 Applications of new technology 新技术应用

- Base isolation
  隔震
- Vibration mitigation
  耗能减振
- New materials
  新材料
- New walls
  新墙体
- Recycle of collapsed building materials
  建筑垃圾利用
- New energy
  新能源

By May, 2012, all of 29,692 projects and ￥865.8B($140B) budget for the seismic recovery have been finished in whole Sichuan Province.

截止2012年5月，四川省纳入国家灾后恢复重建总体规划的29,692个项目已完工99%，概算投资8658亿元已完成投资99.5%

内部讲义，请勿扩散，版权归演讲者所有

进一步强调的几点建议

1. 工程防御、抗震能力

进一步明确我国防震减灾工作指导思想，强化我国防灾减灾工作以防御为主的常态化管理，切实提高土木工程及其基础设施的抗震能力

2. 活动断层调查、地质灾害防御

加强强震动观测与预警、人口密集区域活动断层调查、以及西部高烈度山区城镇地质灾害及其次生灾害的监测、预警、防治和规避规划工作，并从国家区域层面开展大区域抗震防灾综合防御体系的规划建设

3. 中小学建筑和医院等救灾关键建筑抗震标准

尽快建立完善的中小学建筑和医院等救灾关键建筑的抗震防灾常态化管理体系与机制。

内部讲义，请勿扩散，版权归演讲者所有

4. 村镇建筑、中小城市建筑、古建筑

- 明确各级政府在农房建设中的职责和义务，尽快建立起我国村镇建筑抗震防灾监管体系和保障体系，切实提高我国村镇建筑抗震防灾能力；
- 中小城镇防震减灾工作应与城镇化、老城区改造和新农村建设紧密结合，确保中小城镇建筑抗震能力达到与大城市相同的水平；
- 增加文化遗产建筑抗震防灾科学研究的投入，完善文化遗产建筑保护法律法规。

5. 水库群抗震防灾

尽快建立流域水库群的地震风险评估体制，提高大坝工程的整体抗震水平。

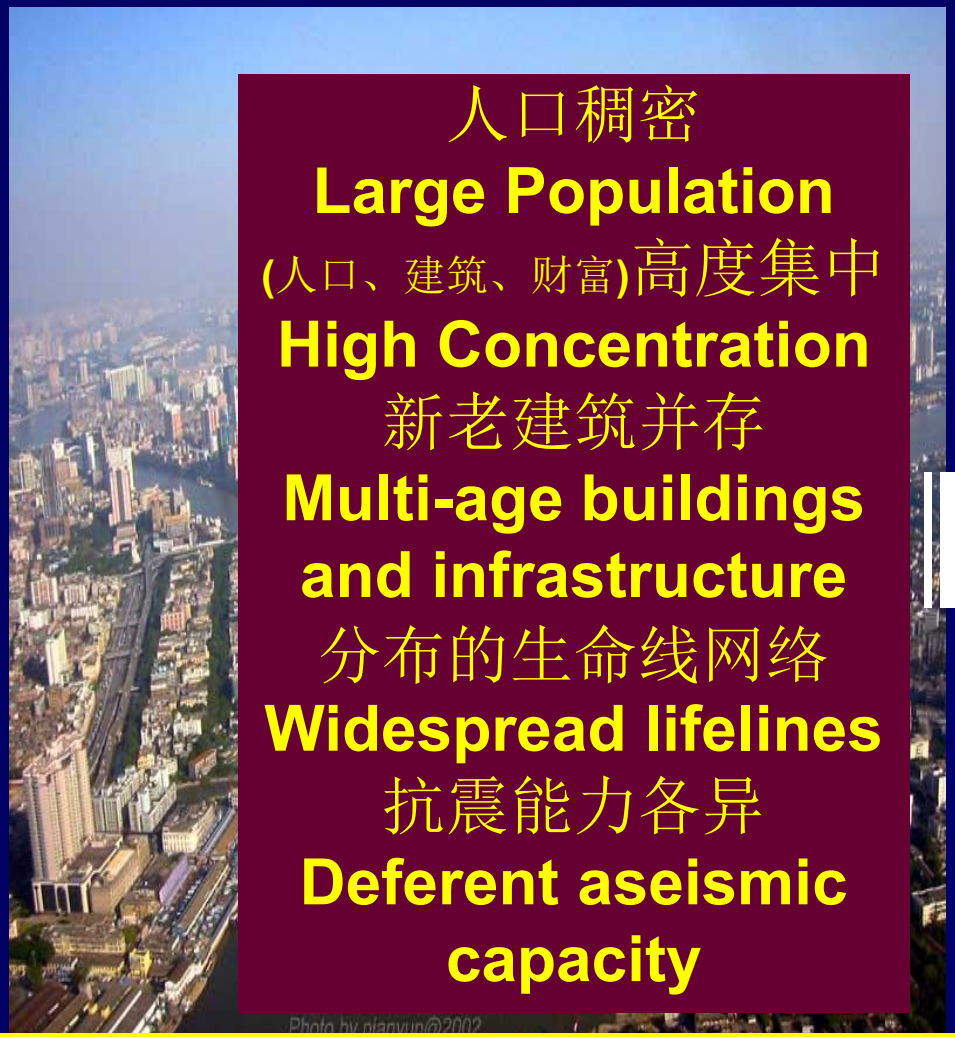
内部讲义，请勿扩散，版权归演讲者所有

II. Earthquake Disaster Prevention of Urban Engineering in China

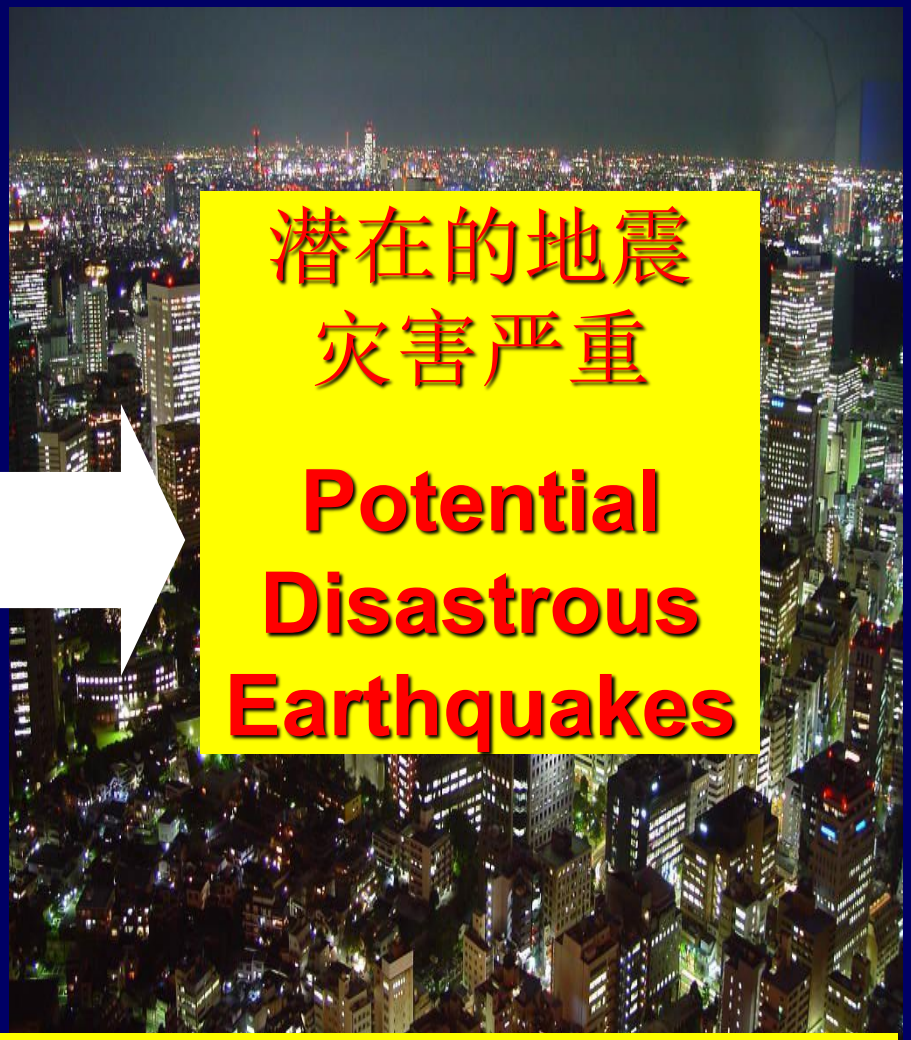
城市工程的地震灾害防御

内部讲义，请勿扩散，版权归演讲者所有

中国现代城市特点 Modern Cities in China



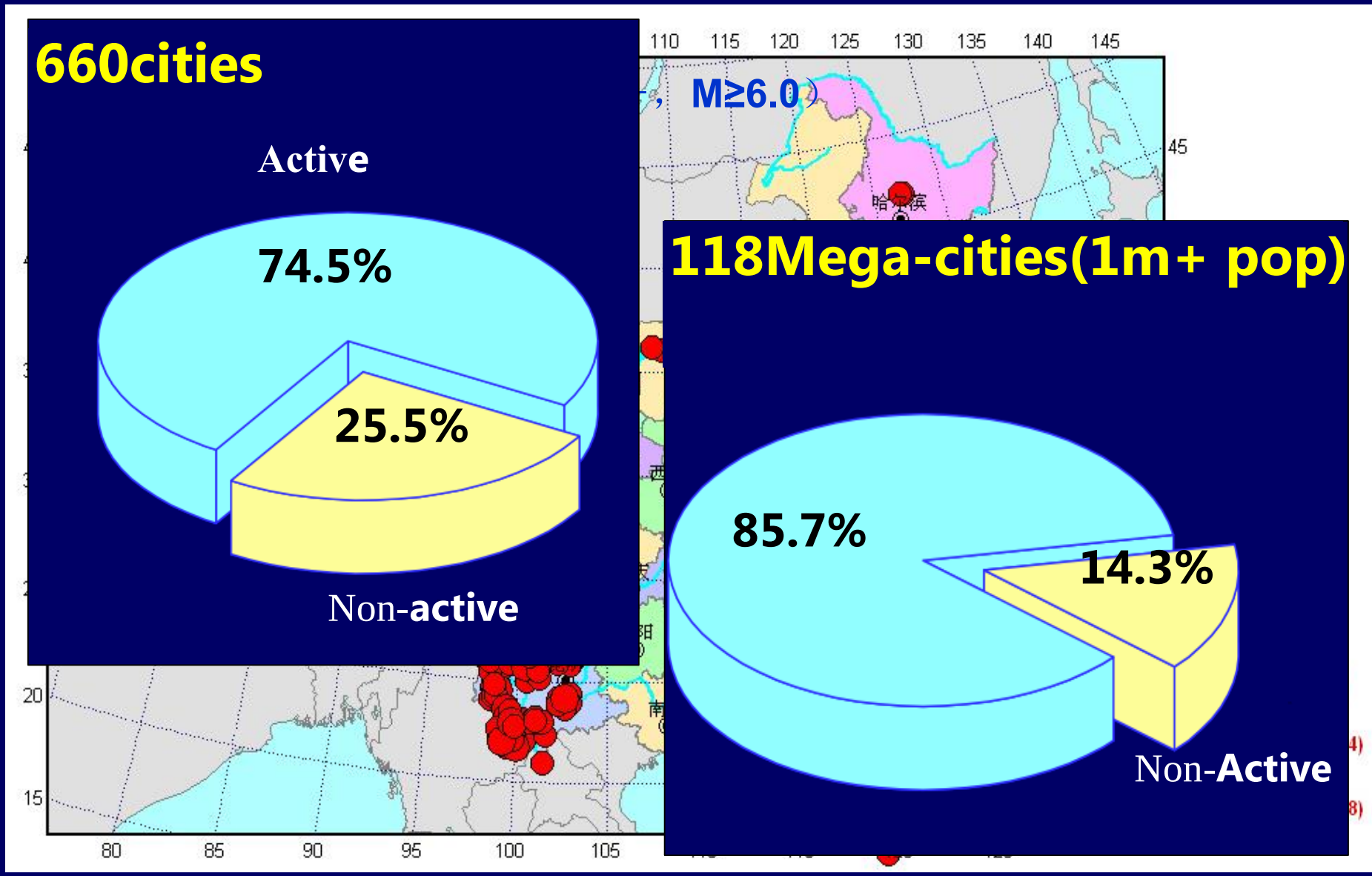
人口稠密
Large Population
(人口、建筑、财富)高度集中
High Concentration
新老建筑并存
Multi-age buildings and infrastructure
分布的生命线网络
Widespread lifelines
抗震能力各异
Deferent aseismic capacity



潜在的地震灾害严重

Potential Disastrous Earthquakes

No country like China, so many cities, in which so large population and high concentration



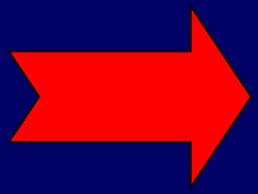
内部讲义，请勿扩散，版权归演讲者所有

到2020年
By 2020……

京津环渤海
Beijing metro

近300年平均每44年
发生1次7级以上大地震
M7 earthquake every 44 yrs
in the last 300 years

长江三角洲
Shanghai metro



5% Land 国土面积
40% Population 承载人口
65%GDP
90% Trade Value 进出口总值

珠江三角洲
Canton metro

历史上多次发生6级以上强震
M6+earthquakes

内部讲义，请勿扩散，版权归演讲者所有

Earthquake Collapse and Control of Urban Engineering

Research Period: **2007.1－2008.12**
PI: Zifa WANG

Research Period: **2009.1－2011.12**
PI: Jinping OU

Funded Sum: ￥28 Million

Institute of Engineering Mechanics
China Seismology Administration Bureau

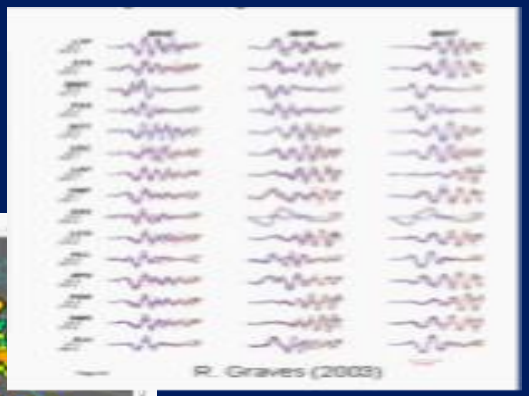
© 2006 Risk Management Solutions, Inc.
CONFIDENTIAL
R M S
内部讲义，请勿扩散，版权归演讲者所有

Key problem 1. Modeling and prediction of near-fault strong ground motion

近场强地震动场建模与预测

Seimic observation & statistical models

强震观测、统计建模



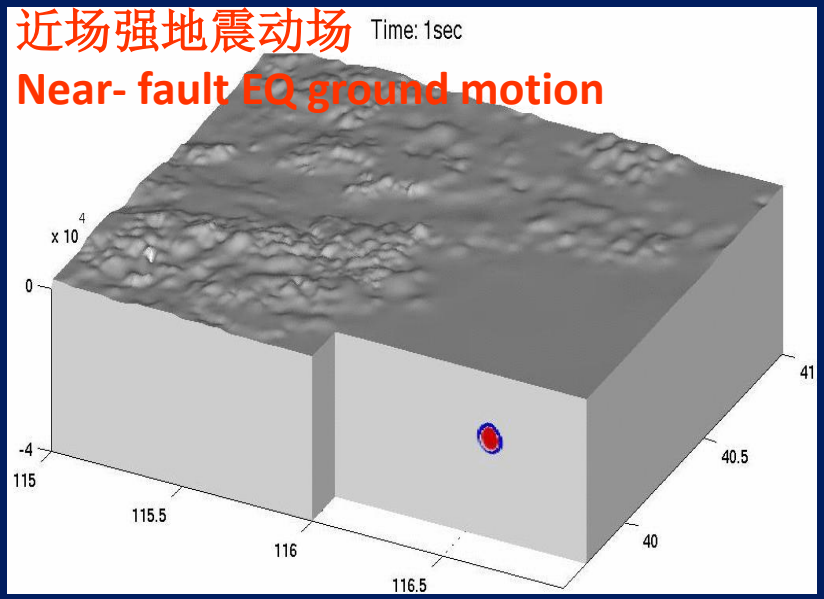
Challenging Issues:

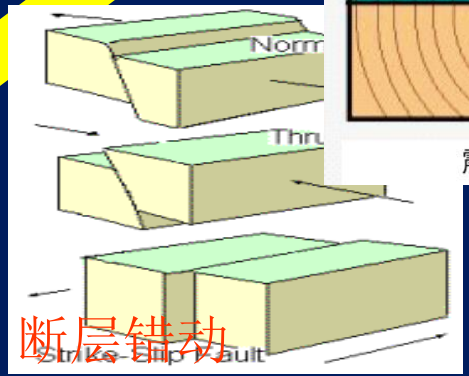
- Hypocenter identification and mo
- 震源[illegible]模
- Wave propagation modeling and simulatio
- 地震波动模
- Identific[illegible]and verification

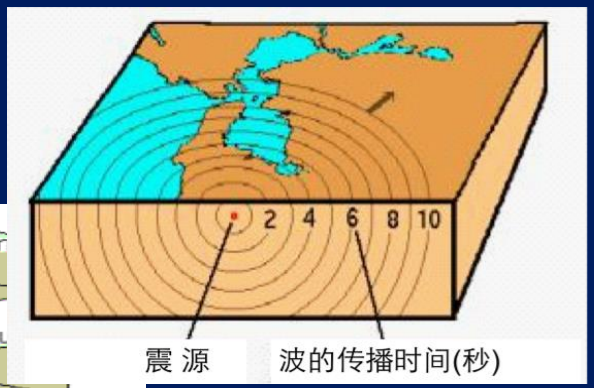
相互验证和反演

Wave propagation modeling and simulation

地震波传播建模模拟



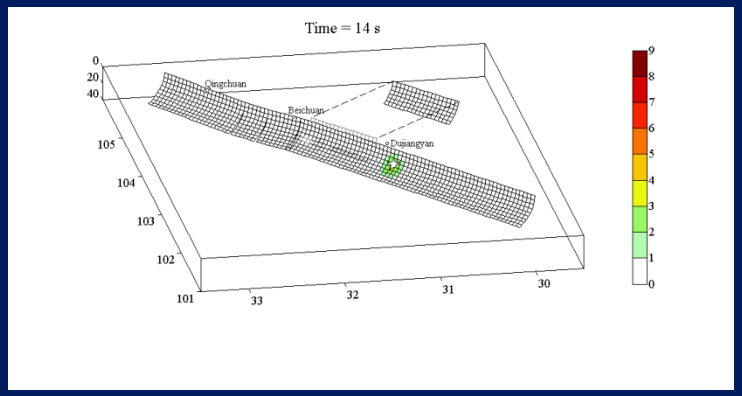


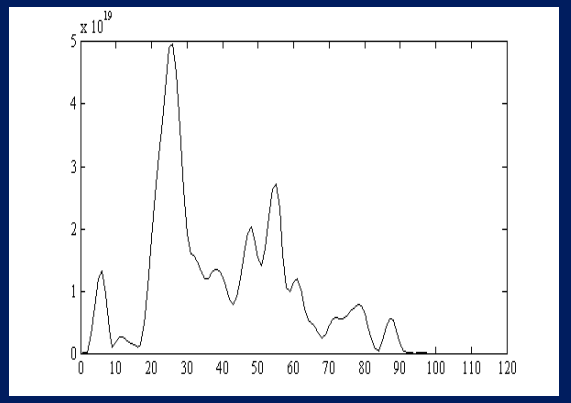


内部讲义，请勿扩散，版权归演讲者所有

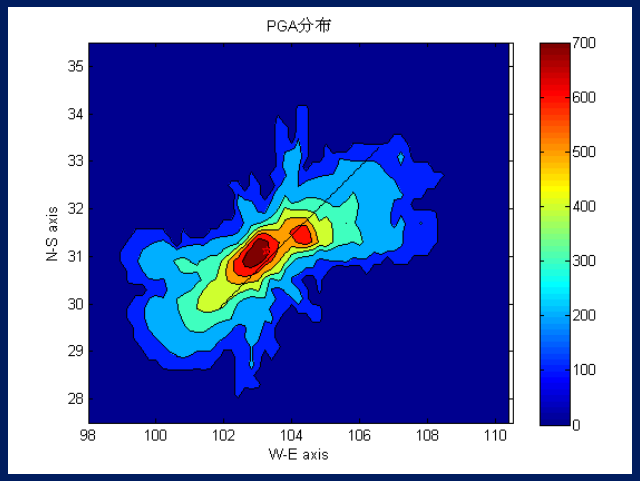
◆ Simulation and verification of Wenchuan earthquake ground motion field

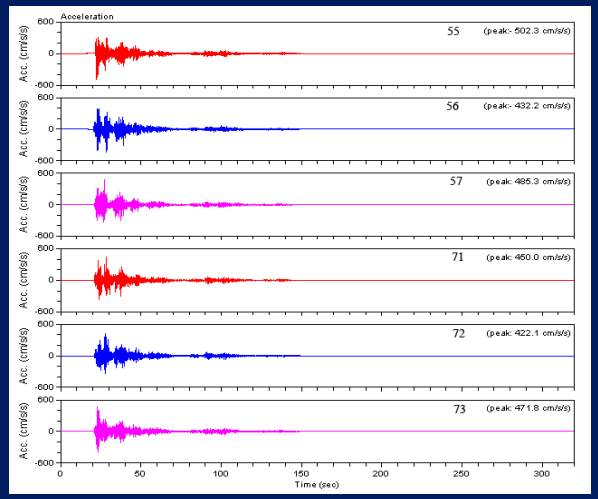
汶川地震动场的模拟与验证

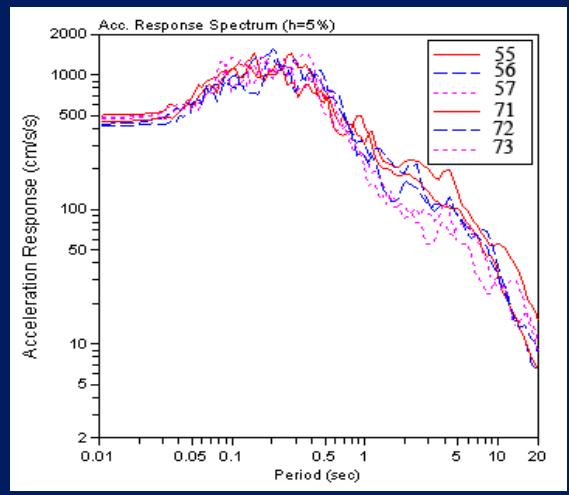




Hypocenter process 震源破裂过程



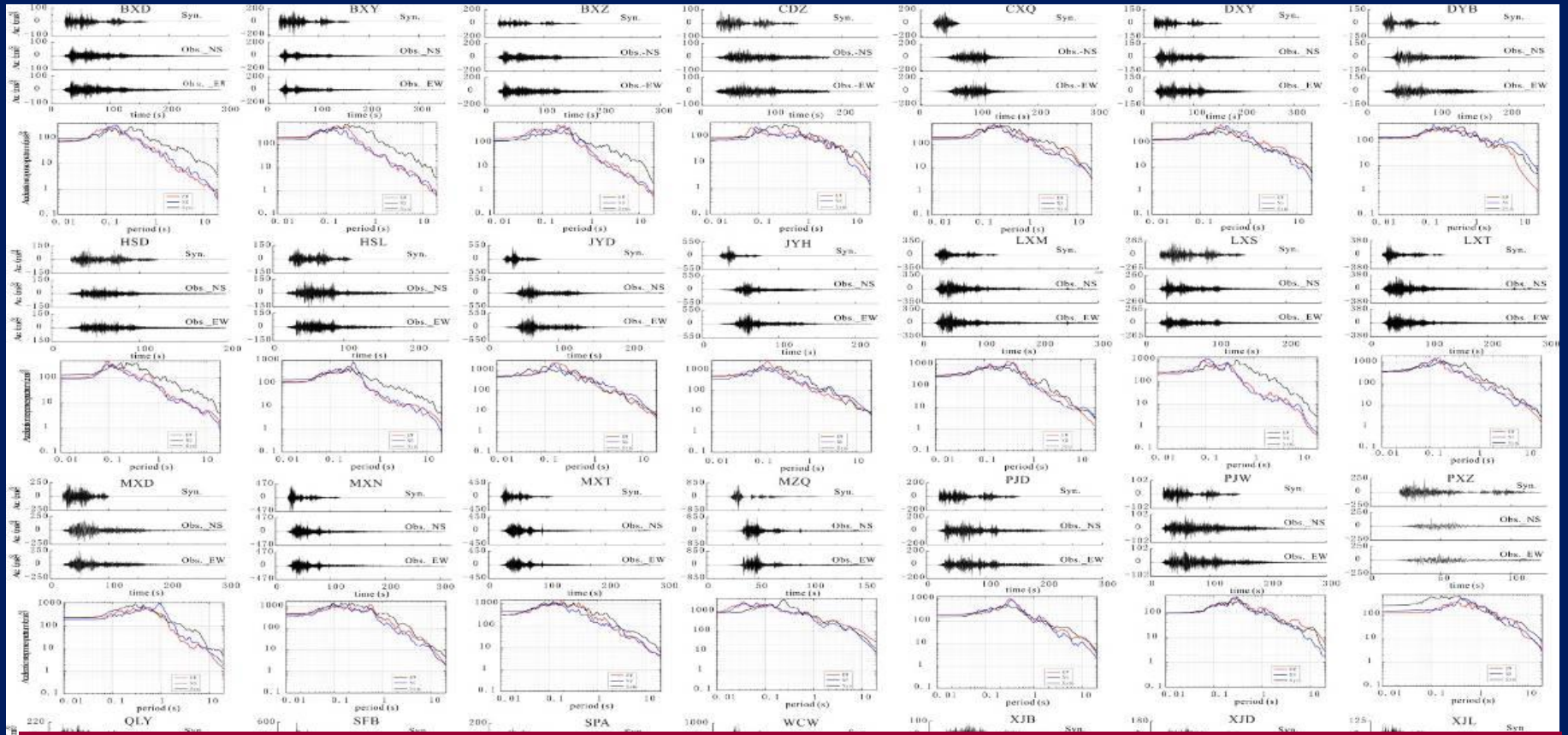




Simulated maximum

Time history and response spectrum

内部讲义，请勿扩散，版权归演讲者所有



Good consistency, but the simulated is higher than the observed value in long period for part of records

模拟与记录结果具有好的一致性，但长周期的模拟结果明显高于记录结果

Observed and simulated comparison of response spectrum

汶川地震地震动的模拟与观测记录结果的对比

(28 records near the fault ）

内部讲义，请勿扩散，版权归演讲者所有

Key problem 3: Seismic Disaster chain modeling and simulation of urban systems

城市复杂系统地震灾害链模型与模拟分析

Key problem 2: Seismic Damage and collapse simulation and aseismic capacity evaluation of urban engineering

城市工程地震损伤破坏模拟与评估预测

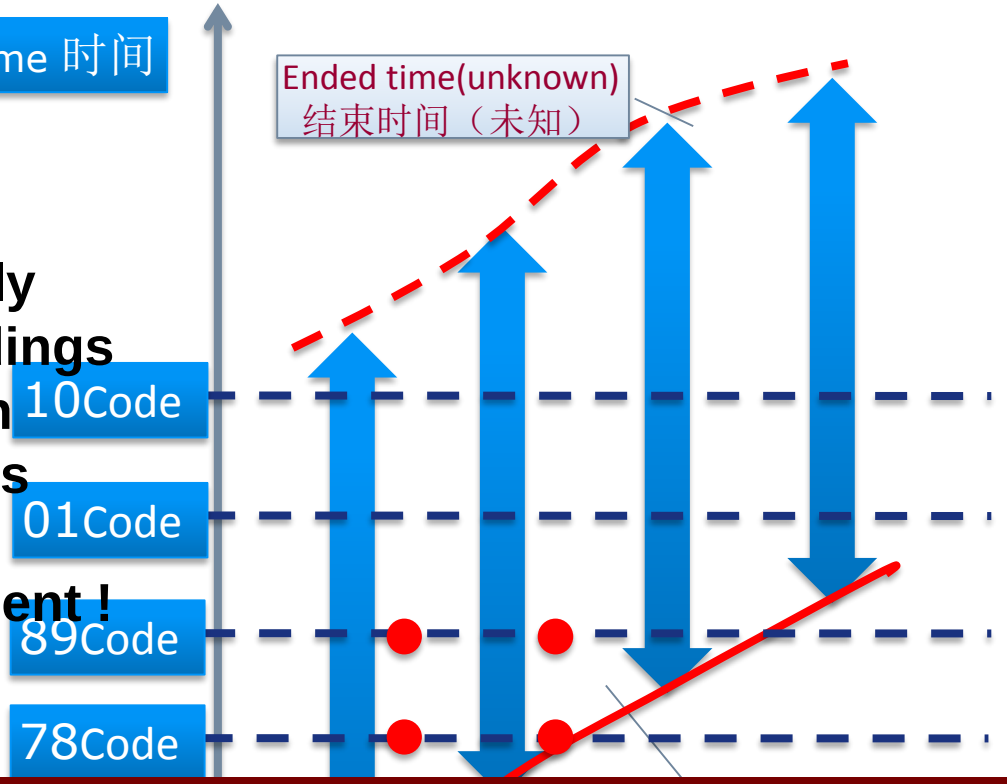
内部讲义，请勿扩散，版权归演讲者所有

Seismic damage simulation and capacity evaluation of aging buildings
城市多龄期建筑地震损伤破坏模拟与评估预测

(Multi-age) aging Buildings

A city is the place historically accumulated: different buildings were built in different age, in which S&T and design codes in earlier ages would be different as well as insufficient !

城市多龄期建筑



◆**Different codes—— Original difference**

设计标准差异——先天抗震能力缺陷

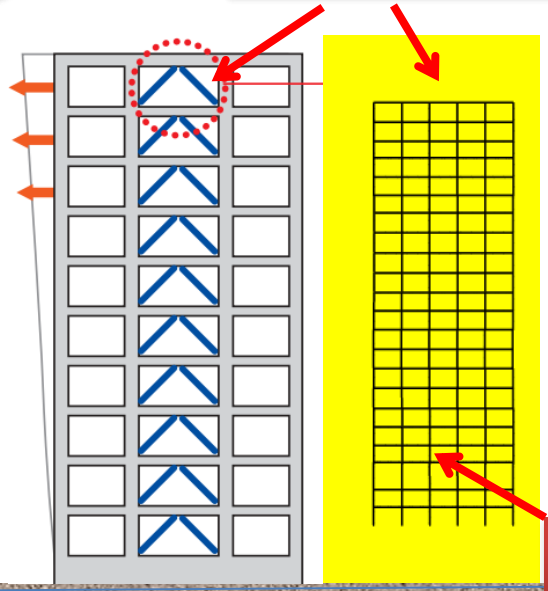
◆**Aging effectiveness——**Deterioration

龄期效应——抗震能力衰减

内部讲义，请勿扩散，版权归演讲者所有

Seismic Damage and collapse simulation and evaluation of urban engineering
城市工程地震损伤破坏模拟与评估预测

Control Systems
控制系统



Multi-ages
老龄期结构

New Struc.
新建结构

Underground struc. 地下结构

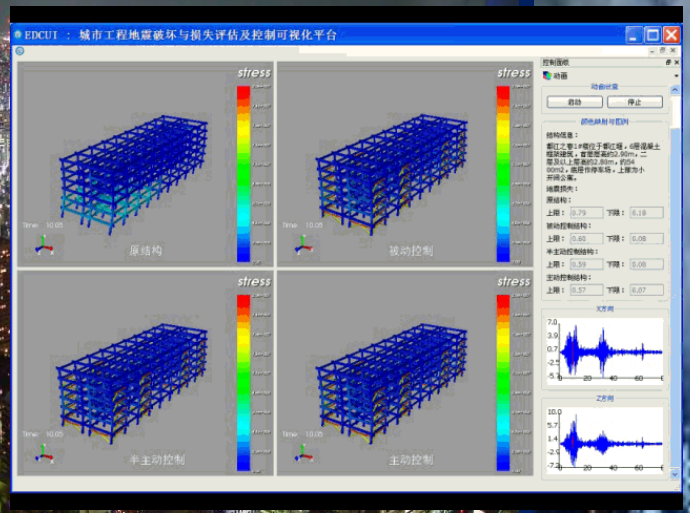
Motion field
城市地震动场

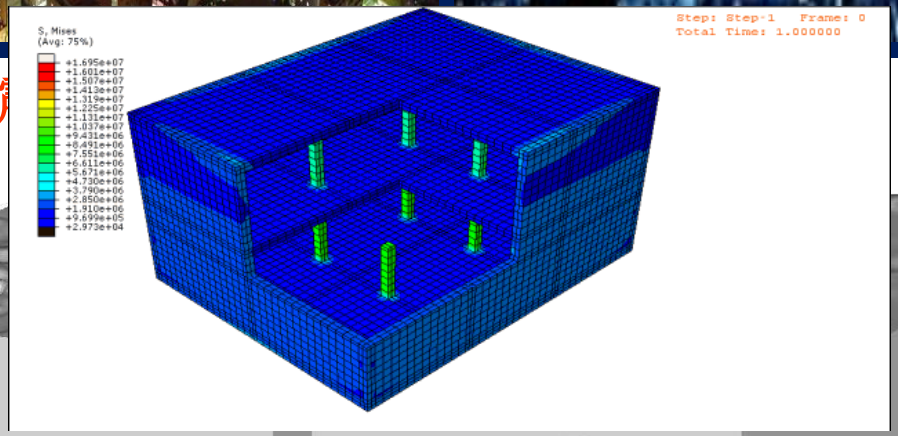
内部讲义，请勿扩散，版权归演讲者所有

城市工程地震破坏模拟与预测

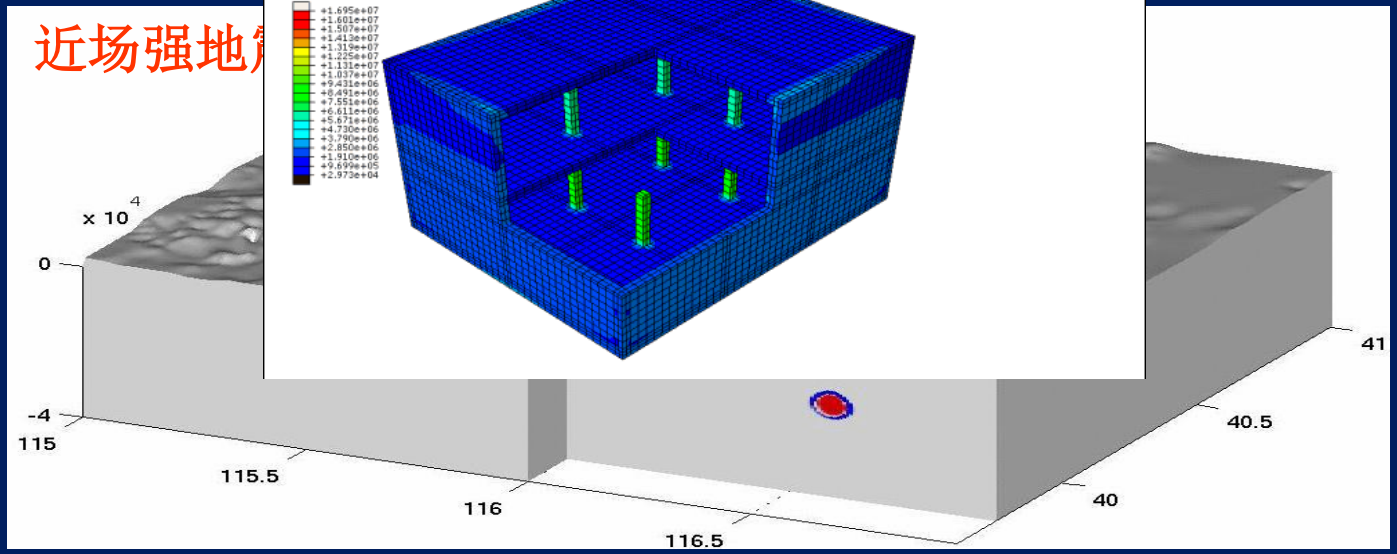
- 单体建筑震害预测方法
- 群体建筑震害预测方法

- 城市地下结构地震破坏精细化建模模拟
- 城市重要建筑地震破坏与控制精细化建模模拟





近场强地震



近场强地震动场模拟

内部讲义，请勿扩散，版权归演讲者所有

城市震害模拟与预测——大规模城市建筑工程地震灾害模拟预测

1、城市建筑单体地震破坏预测方法

大量震害资料统计回归

- 考虑影响结构抗震性能的结构震害影响因子的单体结构震害指数

破坏等级	基本完好	轻微破坏	中等破坏	严重破坏	毁坏
震害指数中值	0	0.2	0.4	0.7	1.0
震害指数的上限	[0，0.1]	(0.1,0.3]	(0.3,0.55]	(0.55,0.85]	(0.85,1.0]

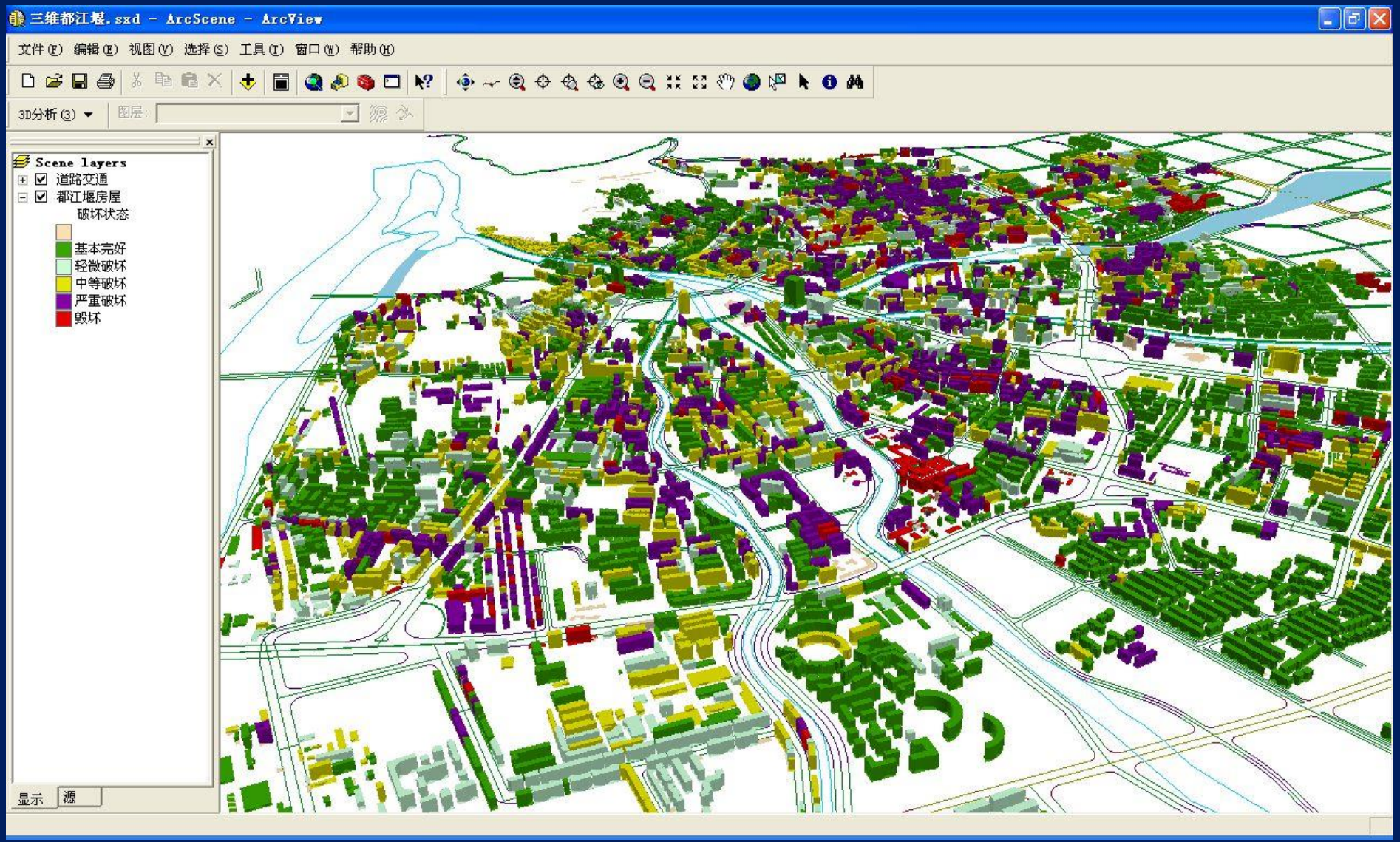
2、城市建筑群体地震破坏预测方法

不需繁重的现场详细的调查工作，不需大量计算参数，即可快速和有效地给出一个城市建筑的地震震害预测结果。

内部讲义，请勿扩散，版权归演讲者所有

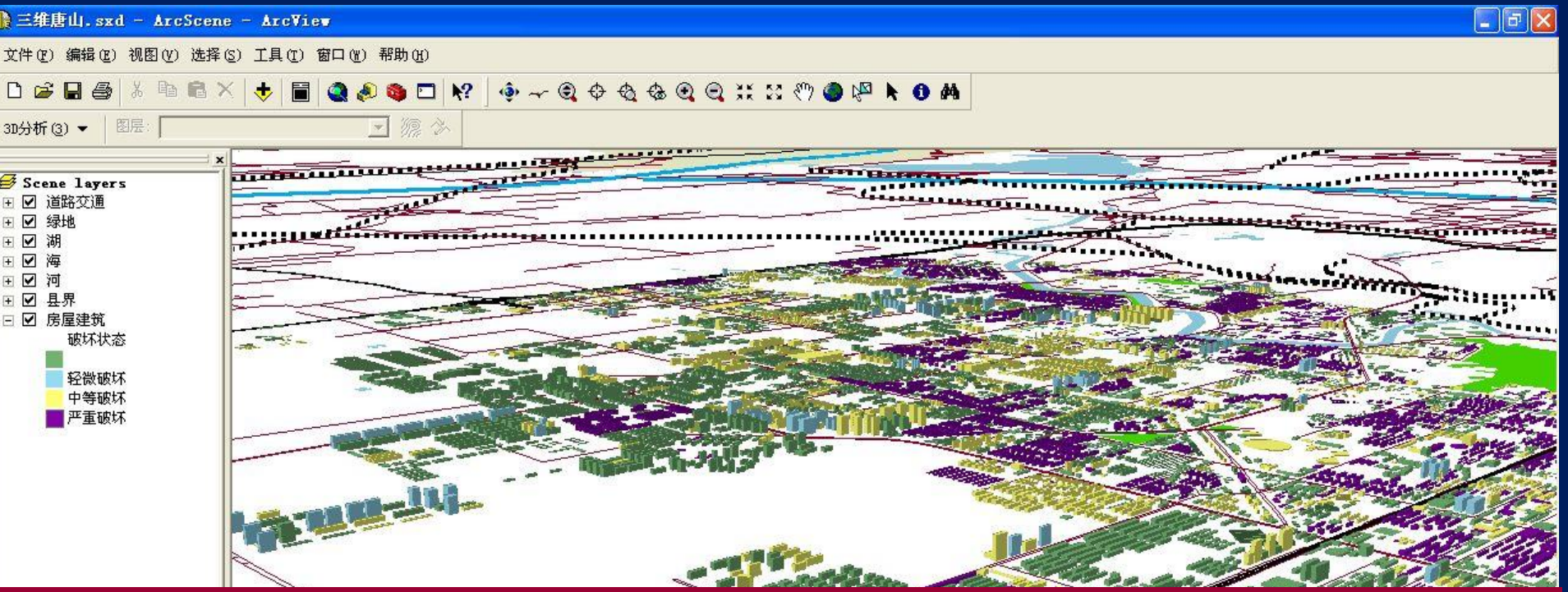
内部讲义，请勿扩散，版权归演讲者所有

实现汶川地震都江堰市震害重演与验证



内部讲义，请勿扩散，版权归演讲者所有

实现唐山市地震震害模拟与预测



如果再发生1976年唐山大地震，新唐山市建筑多数基本完好或轻微破坏，少部分中等破坏或严重破坏，极少发生倒塌

内部讲义，请勿扩散，版权归演讲者所有

III. Earthquake Disaster Prevention of Huge Infrastructure in China

重大工程的地震灾害防御

内部讲义，请勿扩散，版权归演讲者所有

重大工程的动力灾变

执行期：2008.1 - 2015.12

总经费：1.9亿元——1.5(一期)+0.4(2011年评估后)

国际重大合作：NSFC-JST日本：0.06亿元(4 项）

NSFC-NSF/NEES美国：0.18亿元(6项)

——依托本重大计划项目、NSFC国际合作局资助

主管学部：工程与材料科学部

交叉学部：地球科学部、数理科学部、信息科学部

内部讲义，请勿扩散，版权归演讲者所有

总体目标和核心科学问题

2

内部讲义，请勿扩散，版权归演讲者所有

研究背景

❖ **我国重大工程建设的宏大规模居世界之首**

——已经建成或正在建设一大批重大工程

❖ **世界前10座最高建筑，我国6座**

❖ **世界前10座最大跨度斜拉桥，我国7座**

世界前10座最大跨度悬索桥，我国3座

❖ **世界上最大规模的水利工程——我国三峡工程**

世界上最高的拱坝——我国小湾、锦屏

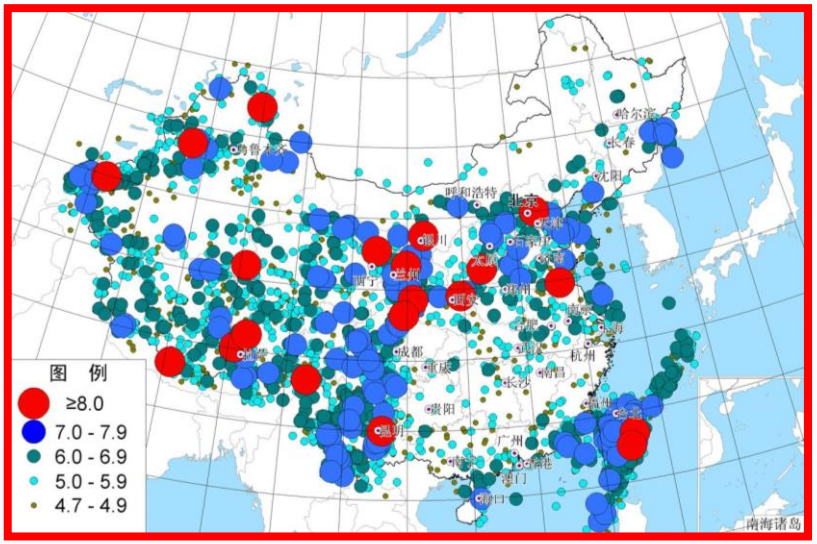
——我国每年重大土木水利工程建设规模超过世界上其它所有国家的总和！

内部讲义，请勿扩散，版权归演讲者所有

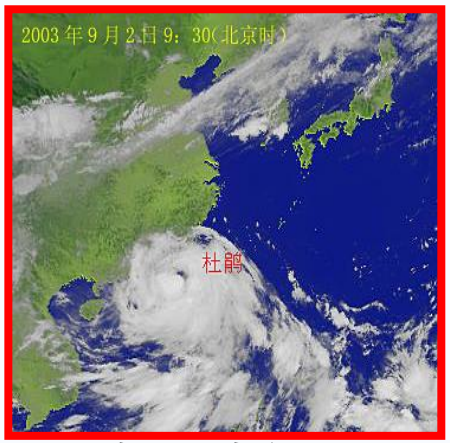
研究背景

❖ **我国重大工程面临严重的地震和台风灾害威胁**

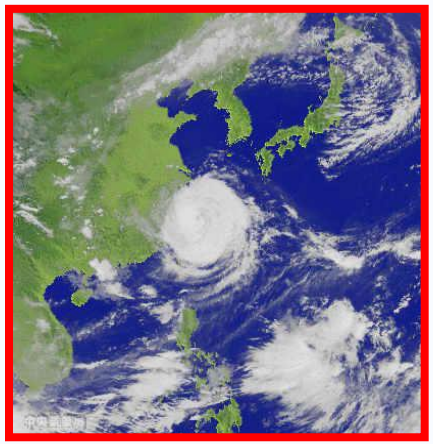
——我国许多重大工程建设在强地震区



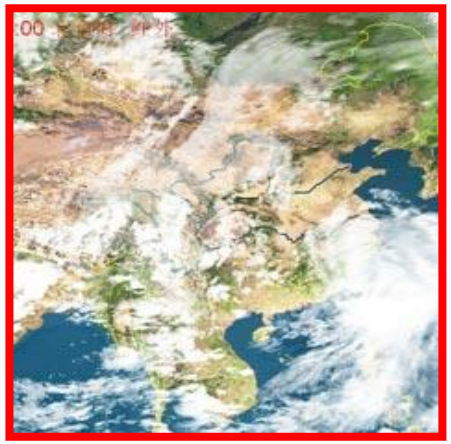
——我国沿海地区台风发生频繁热带气旋（台风）平均每年登陆7次，引发严重的灾害



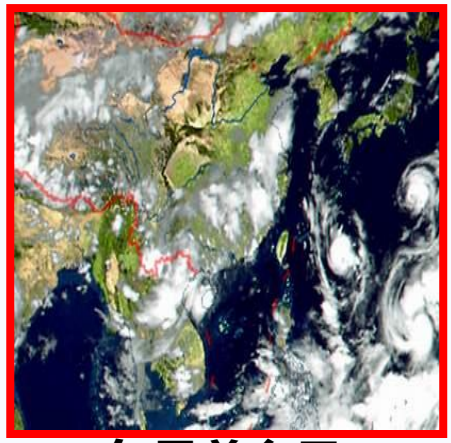
2003年杜鹃台风



2004年云娜台风



2005年海棠台风



2006年桑美台风

内部讲义，请勿扩散，版权归演讲者所有

聚焦的对象、灾种和问题

对象：
重大工程

- 长大桥梁
- 大型建筑（超高建筑、大型空间结构、大型地下建筑）
- 高坝

——关系国计民生和国家经济命脉

灾种：强地震；强风/台风

问题——动力灾变：

- ◆研究重大工程在强地震、强/台风动力作用下的损伤演化和破坏过程
- ◆揭示重大工程的损伤机理和破坏倒塌机制
- ◆建立重大工程动力灾变模拟系统

内部讲义，请勿扩散，版权归演讲者所有

关键与核心科学问题一

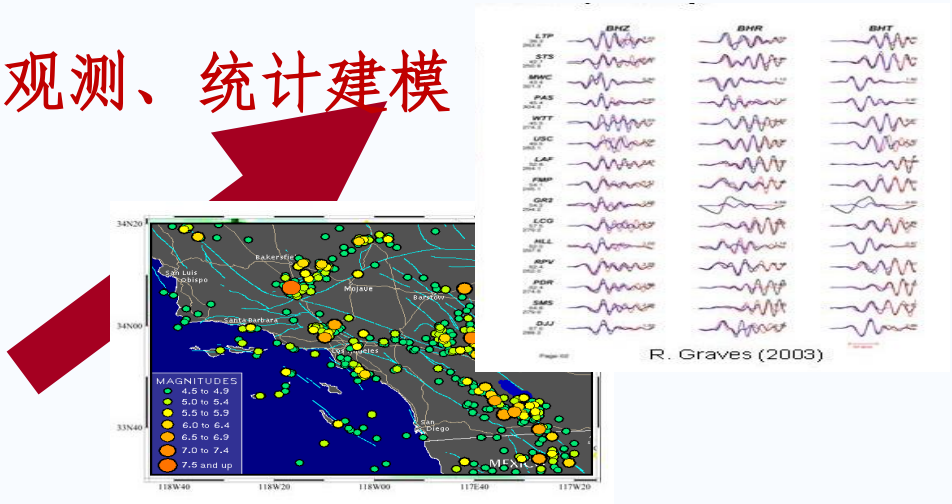
强地震动和强/台风场的特性与规律

- 传播/移动、衰减和空间分布规律
- 统计推断 + 理论建模与数值模拟

内部讲义，请勿扩散，版权归演讲者所有

1.1近场强地震动场建模与预测

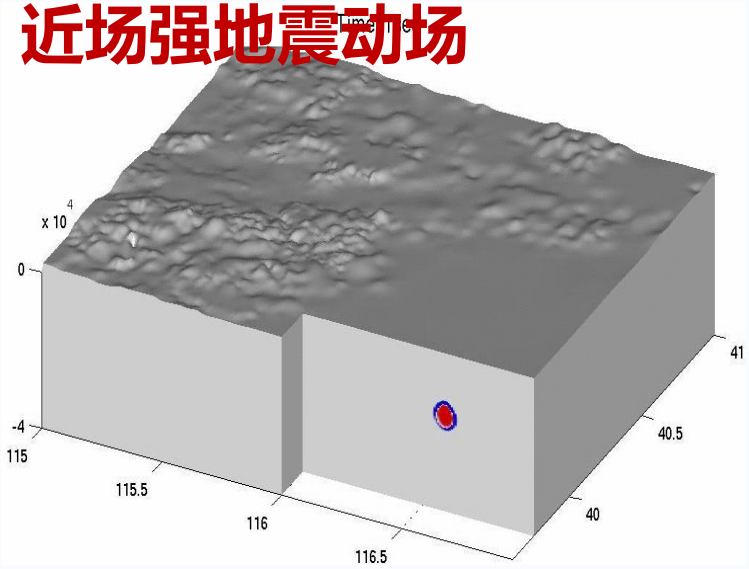
强震观测、统计建模



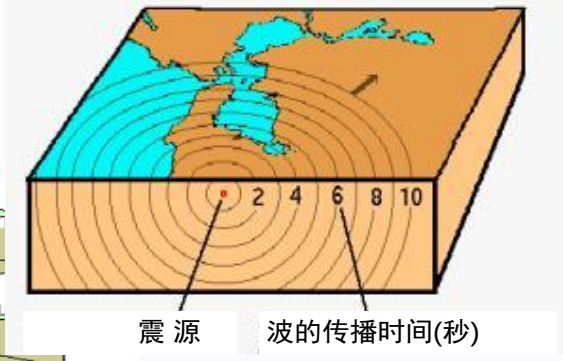
核心科学问题：

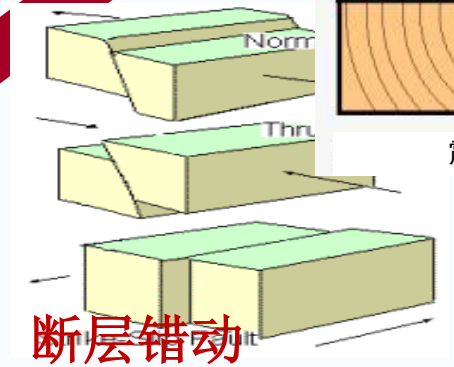
- 震源机制
- 地震波动模拟
- 局部场地影响
- 经验统计与物理建模模拟相互验证和反演

近场强地震动场



地震波传播建模模拟





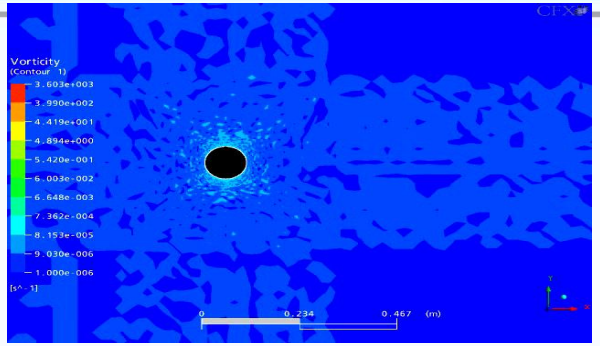
断层错动

内部讲义，请勿扩散，版权归演讲者所有

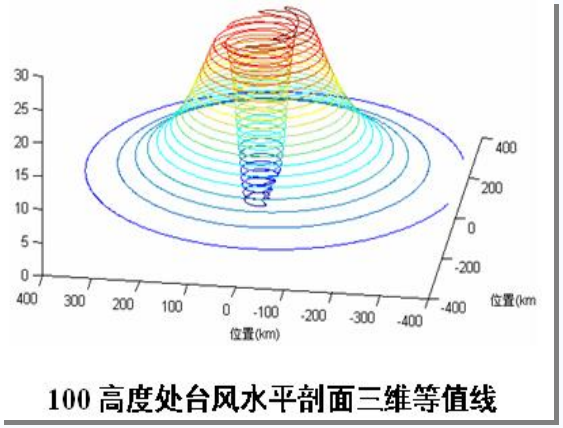
1.2近地强/台风场建模与预测

核心科学问题

空气动力作用：来流、结构振动耦合效应

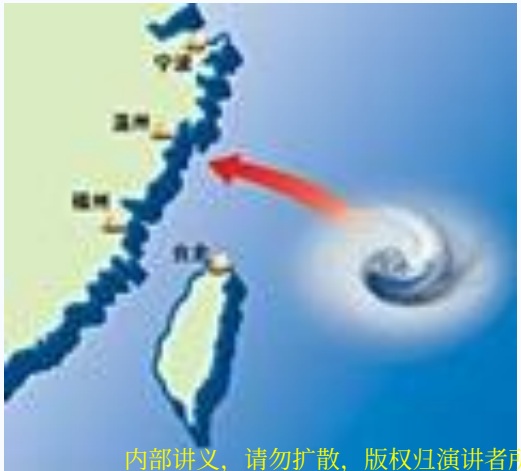


实测建模：近地强/台风场的三维时空分布



100 高度处台风水平剖面三维等值线

数值模拟：台风登陆、移动、地形地貌影响、台风衰减过程的风速分布



内部讲义，请勿扩散，版权归演讲者所有

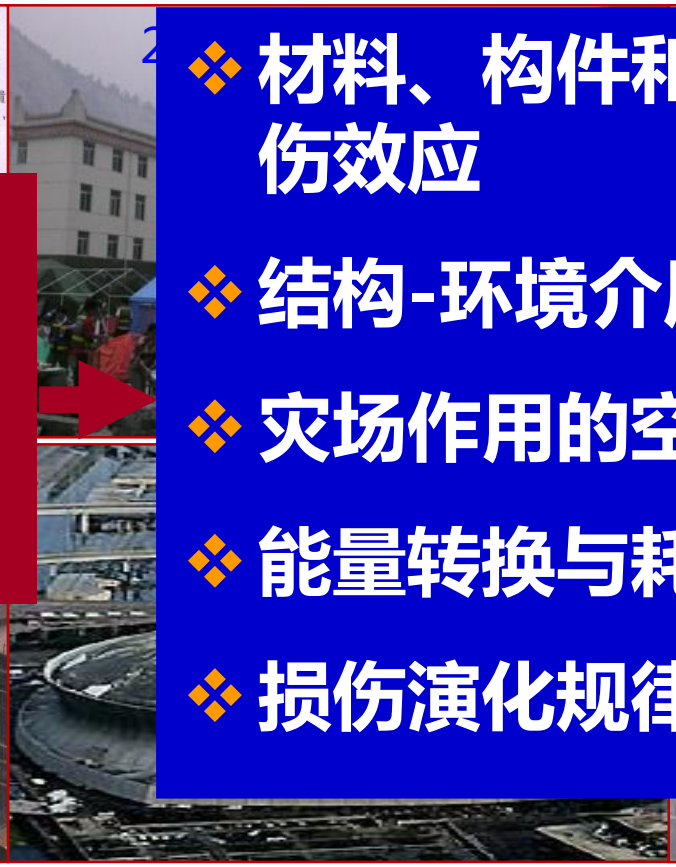
关键与核心科学问题二

- 强地震、强/台风的破坏效应

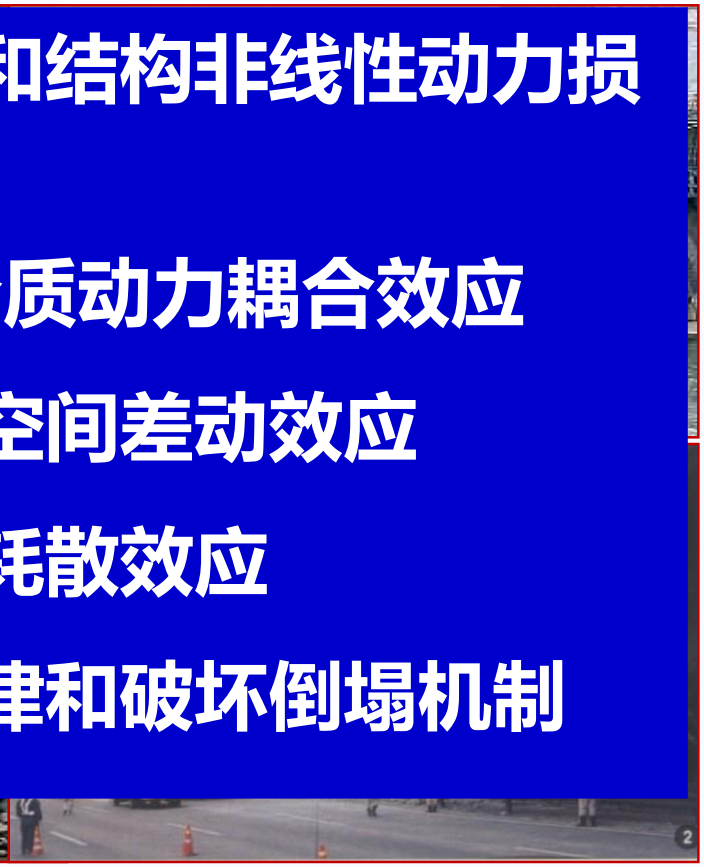
重大工程动力灾变的过程与机理

- 材料、构件和结构非线性动力损伤效应
- 结构-环境介质动力耦合效应
- 灾场作用的空间差动效应
- 能量转换与耗散效应
- 损伤演化规律和破坏倒塌机制

1999年台湾集集地震



2005年美国卡特林娜飓风



1995年日本阪神地震

内部讲义，请勿扩散，版权归演讲者所有

2.1材料、构件和结构的非线性动力损伤与破坏行为

建模与分析

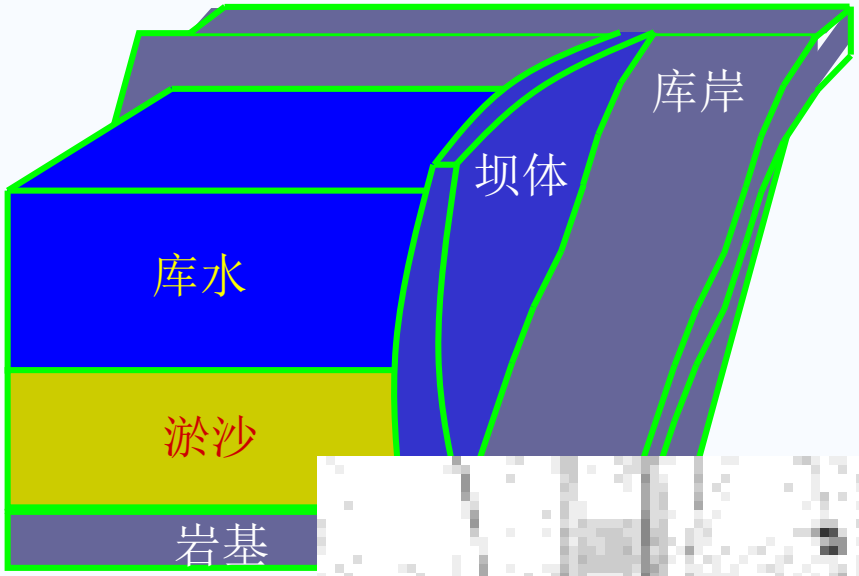
整体结构

构件

材料

2.2 结构-环境多介质强耦合效应

- 强地震作用下： 库水-淤沙-坝体-基岩耦合体系



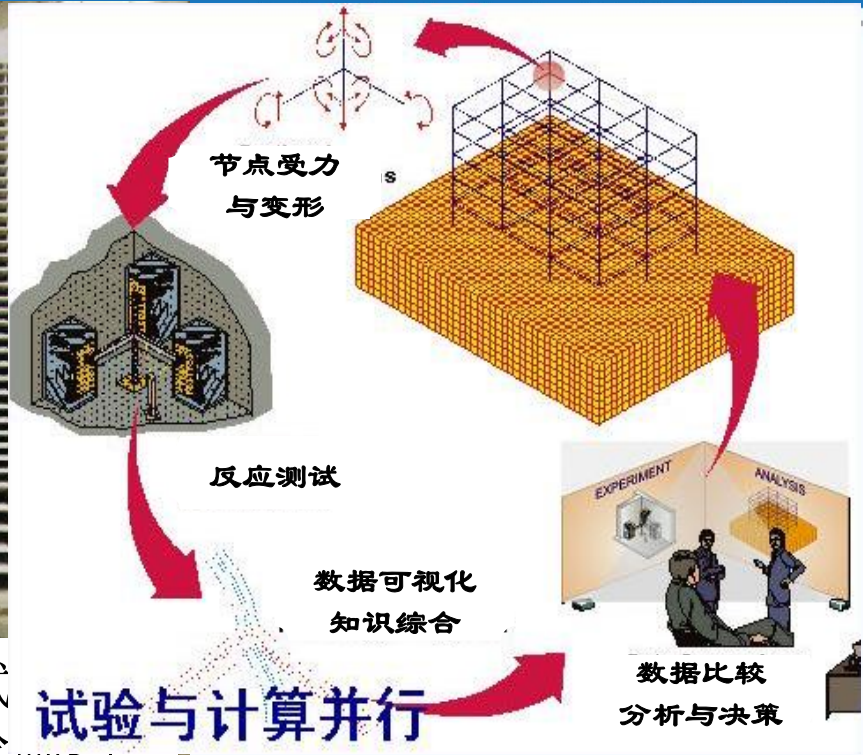
- 大跨桥梁风/雨激振的气/液流-固耦合效应

内部讲义，请勿扩散，版权归演讲者所有

2.3重大工程动力灾变过程的物理和数值模拟

❖难题：

缩尺物理模型试
相似性模拟理论



六层钢筋混凝土结构振动台试验

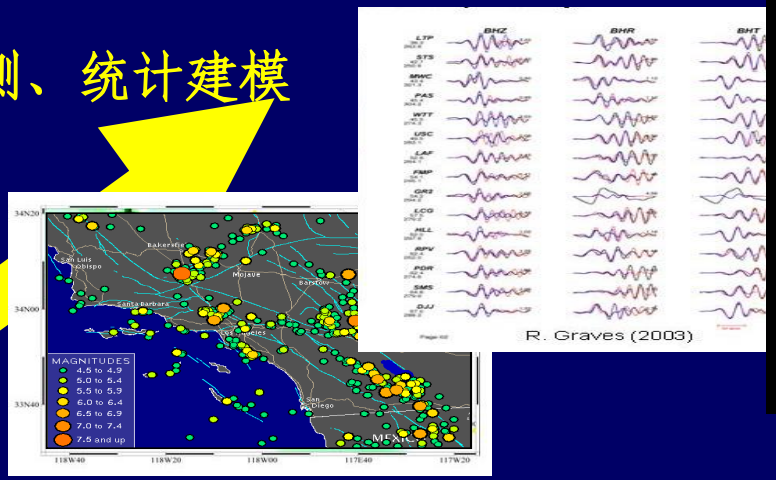
足尺物理模型试验难以实现

前沿：子结构物理模型试验与数值计算并行实时模拟

内部讲义，请勿扩散，版权归演讲者所有

1.1实现了近场强地震动场理论建模、预测与验证
——2008汶川地震动、1999台湾集集地震动

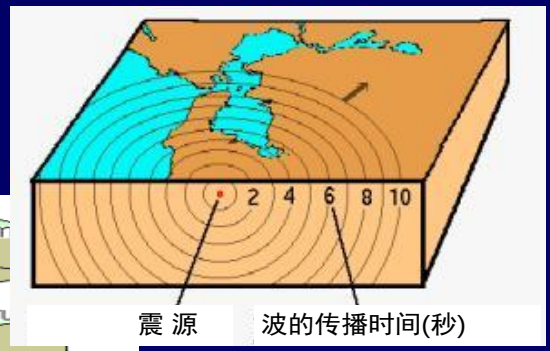
强震观测、统计建模



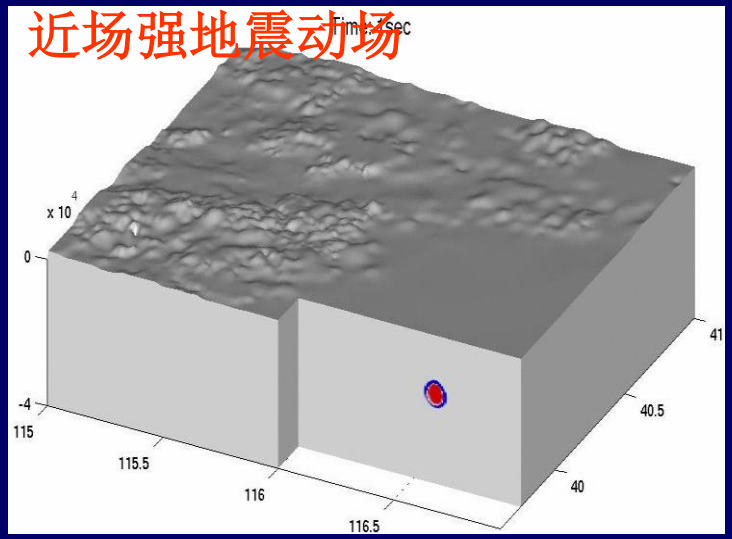
突破的核心问题：
- 震源识别与建模
- 地震波动模拟
- 大型盆地效应
- 经验统计与物理建模

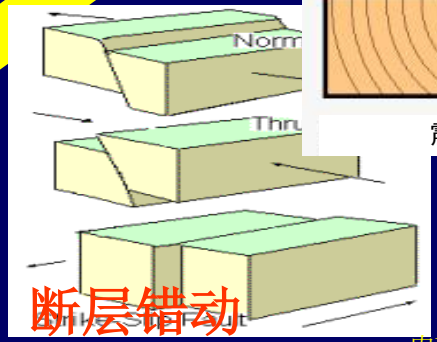
模拟相互验证和反演

地震波传播建模模拟



近场强地震动场



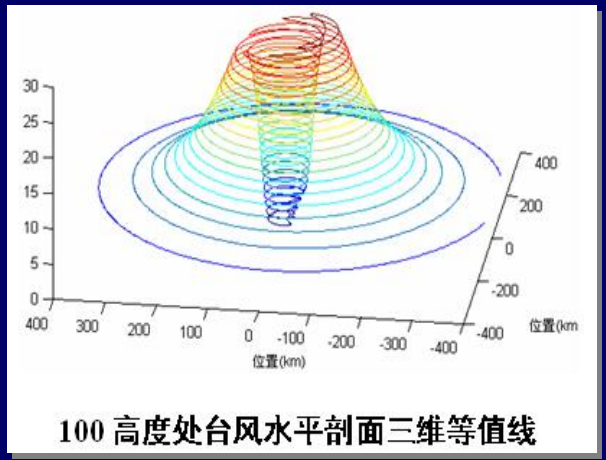


断层错动

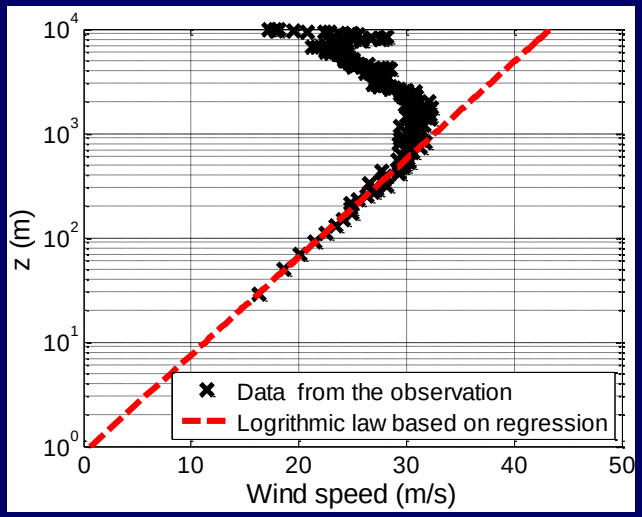
内部讲义，请勿扩散，版权归演讲者所有

1.2实现了近地强/台风场工程化建模、预测与验证
——分布特性与时空模型

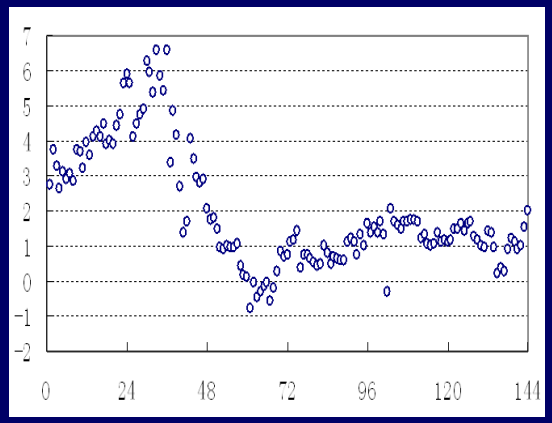
统计分析登陆我国60个台风过程的近地边界层实测数据，建模模拟得到：登陆台风近地层风场结构特性——三维时空分布



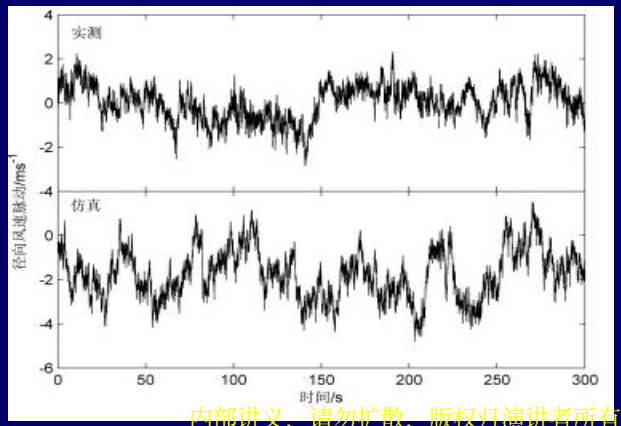
100 高度处台风水平剖面三维等值线



平均风廓线最大风高度和拟合结果


台风过程风攻角变化（度）

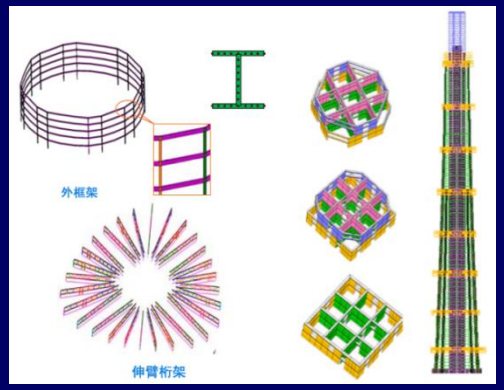
建立台风近地面脉动风功率谱密度理论模型，提出湍流风速脉动理论模型

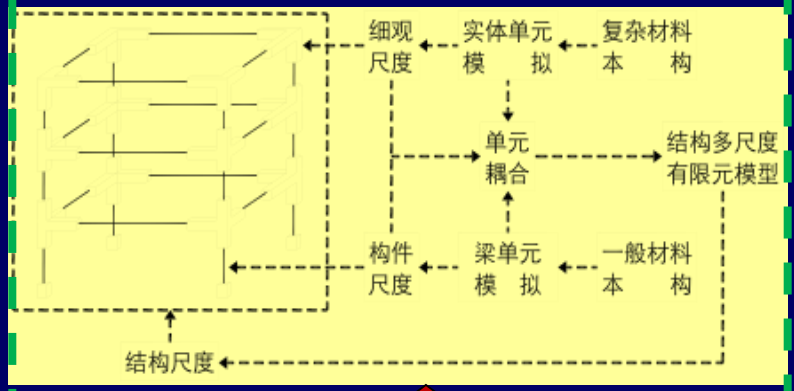


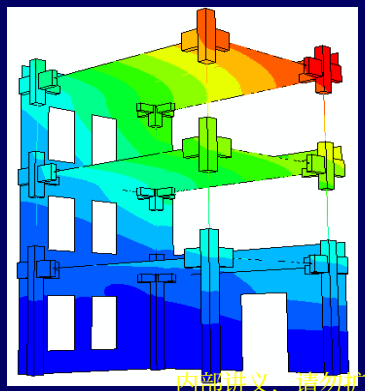
内部讲义，请勿扩散，版权归演讲者所有

2、 Multi-scale models of structural material, members and systems

材料、构件和结构整体的多尺度非线性动力计算模型







内部讲义，请勿扩散，版权归演讲者所有

3、Numerical simulation of seismic damage and collapse of large structures

大型结构地震损伤与倒塌的数值模拟

1E: Earthquake collapse analysis of Beijing Z15 tower with 546m height

Z15塔楼结构高度546米

地下**6**层，约**5**万平米

地上**119**层，约**35**万平米

塔楼外形以“尊”为意象

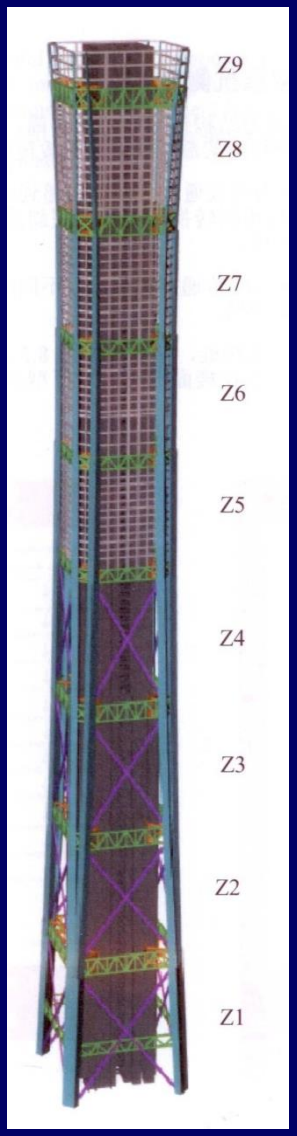
平面基本为方形:

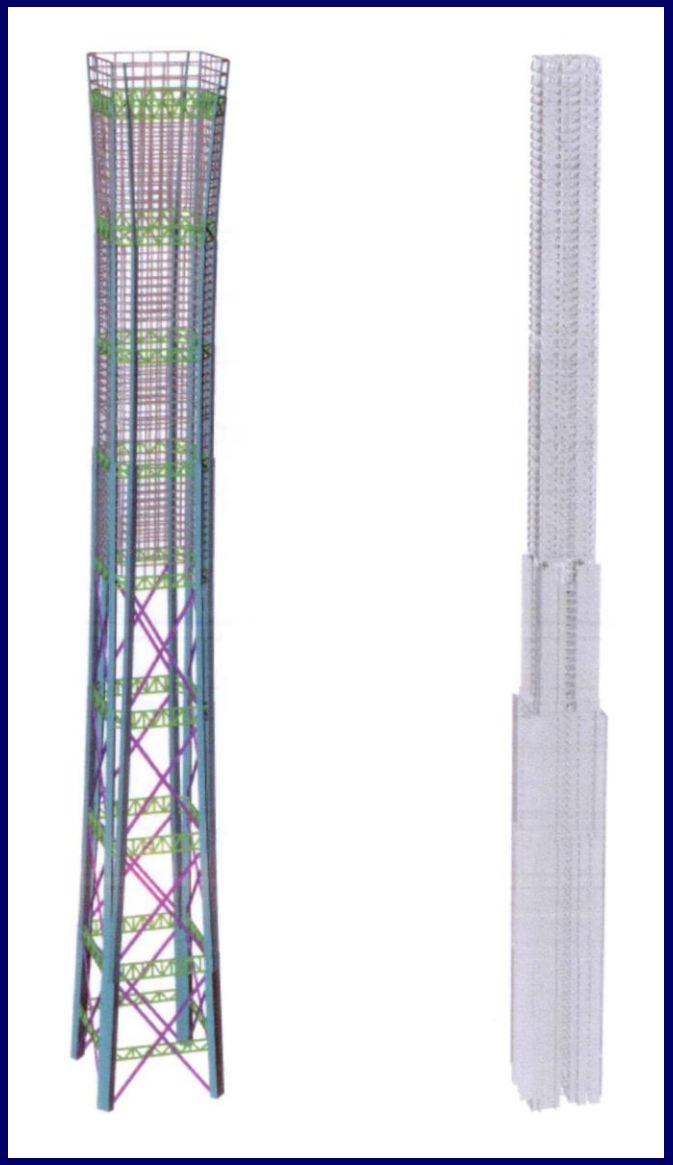
底部约**68m**×**68m**

中上部约**50m**×**50m**

顶部约**60m**×**60m**

内部讲义，请勿扩散，版权归演讲者所有

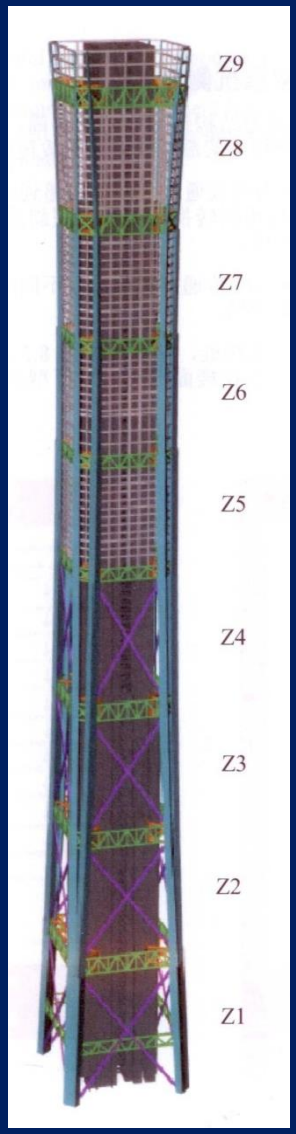


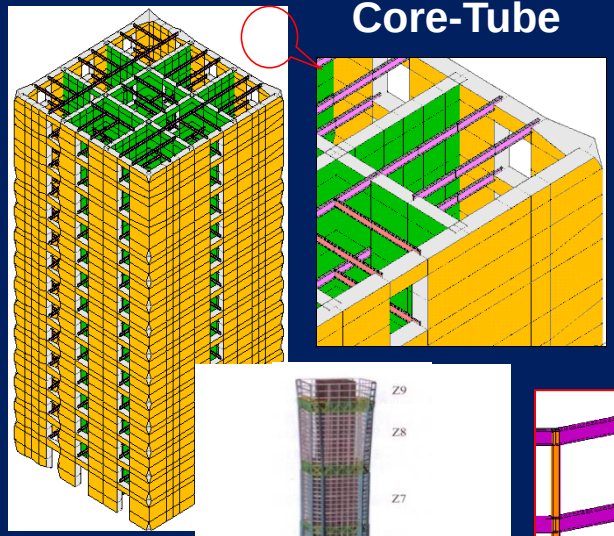


Structure Outside frame The core

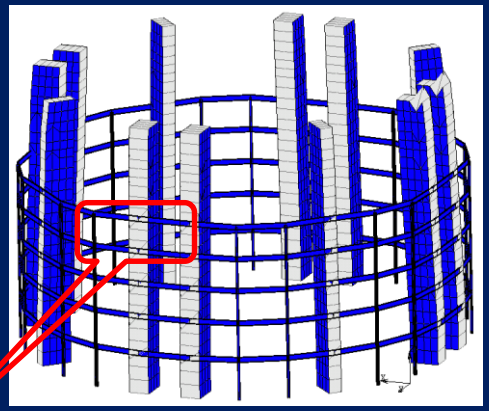
内部讲义，请勿扩散，版权归演讲者所有

Computational Model of Structure
结构计算模型

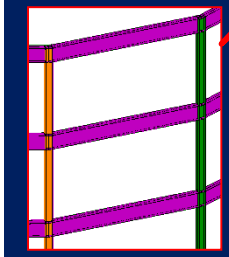




Core-Tube



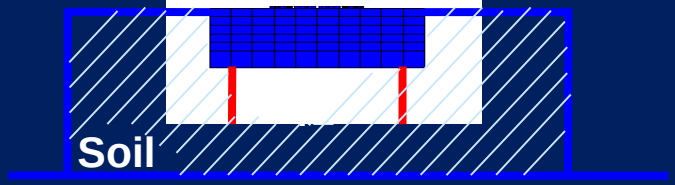
Simplified model for columns



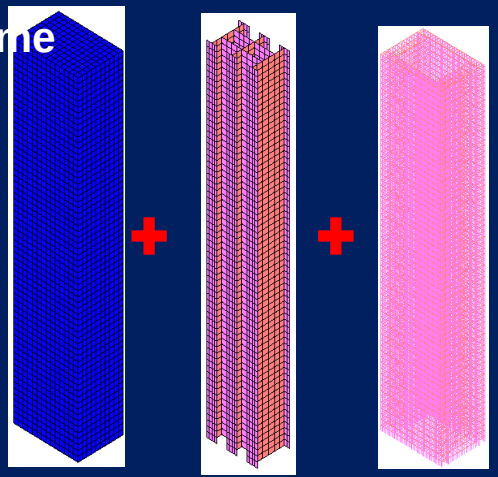
Exterior frame

Fine model for columns

Basement



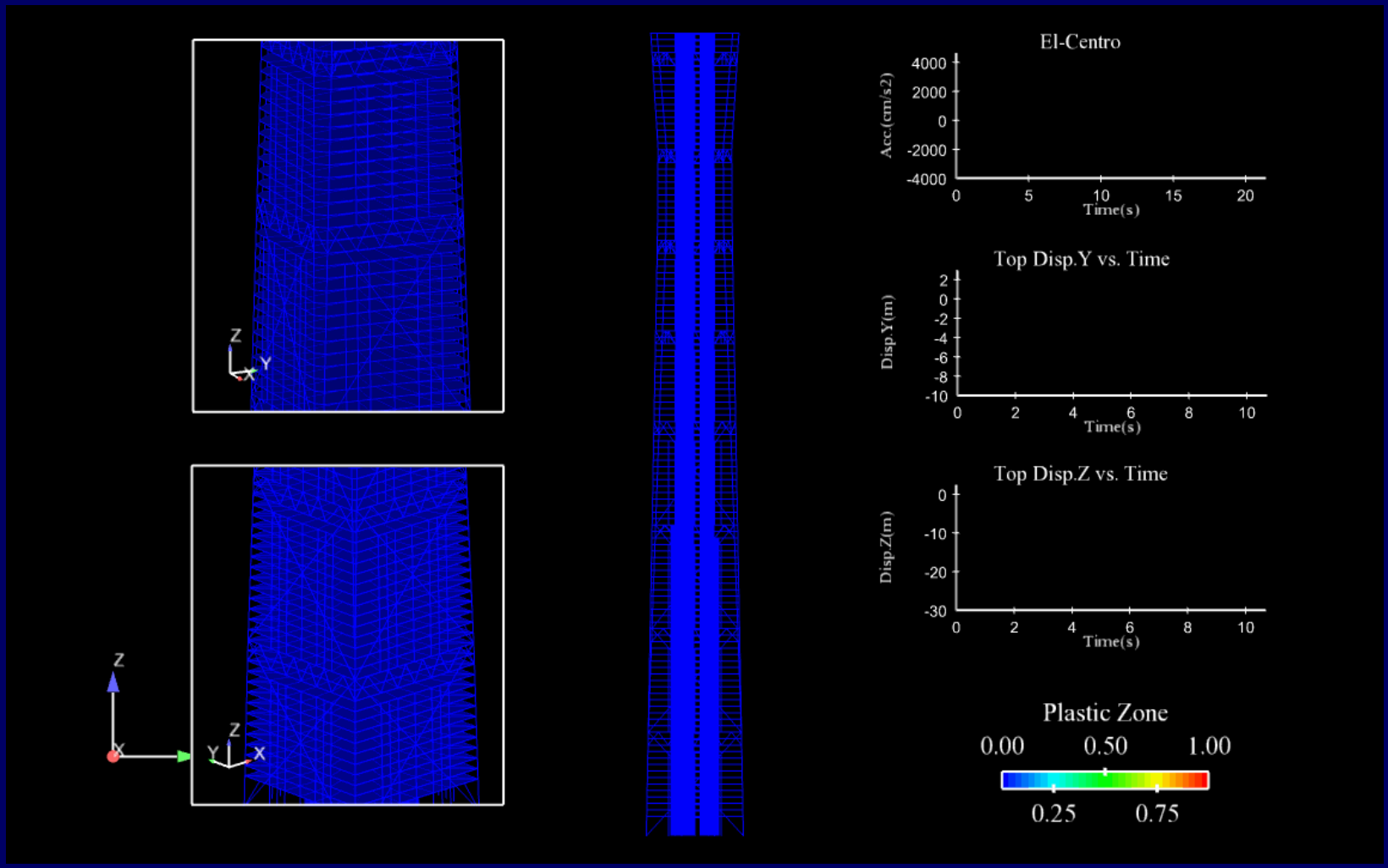
Soil-structure interaction



Concrete Formed steel Rebar

内部讲义，请勿扩散，版权归演讲者所有

Collapse simulation



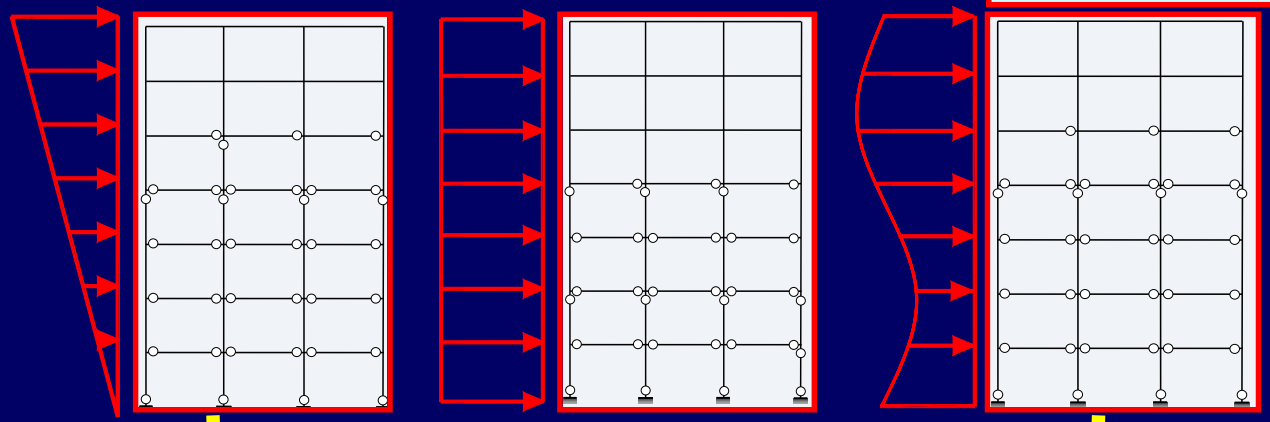
El-Centro EW 1940 **PGA_{scaled} = 3,000 gal** **PGV = 328cm/s**

内部讲义，请勿扩散，版权归演讲者所有

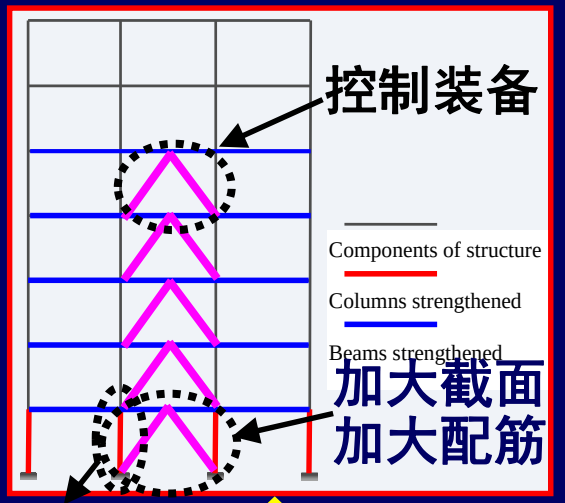
4、Failure modes and their optimisation
失效模式与优化

通过多侧力模式Pushover分析近似反映地震动的随机性对结构失效模式的影响

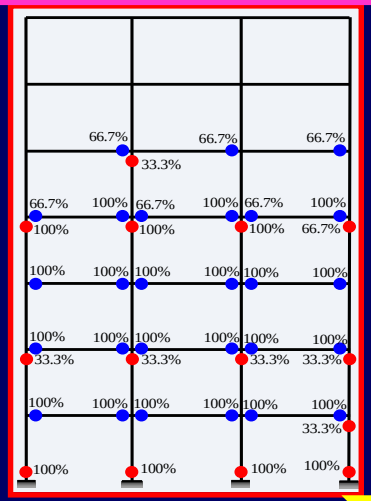
Three modes/结构三种失效模式



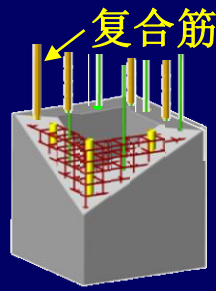
加强策略之三



塑性铰分布概率



+ 失效路径



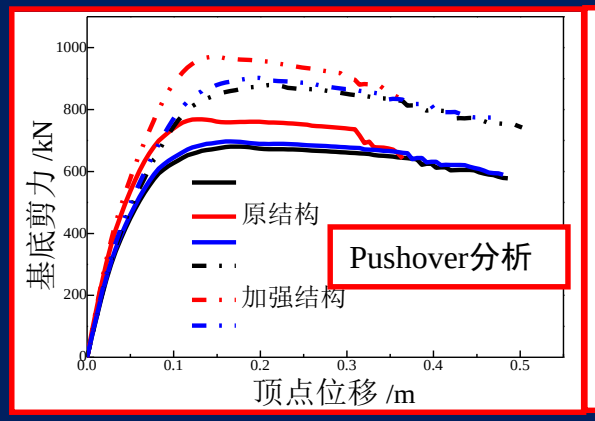
提出了综合考虑失效路径和构件塑性铰分布概率大小来加强结构的失效模式优化方法

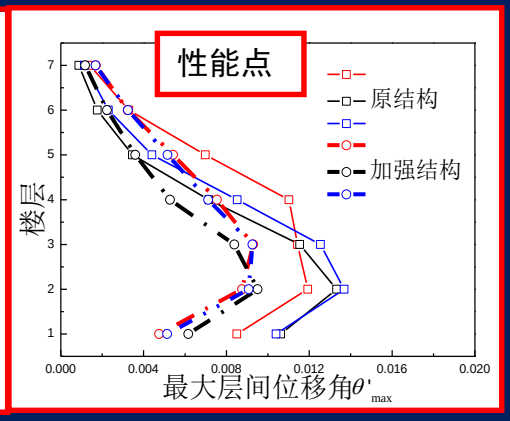
内部讲义，请勿扩散，版权归演讲者所有

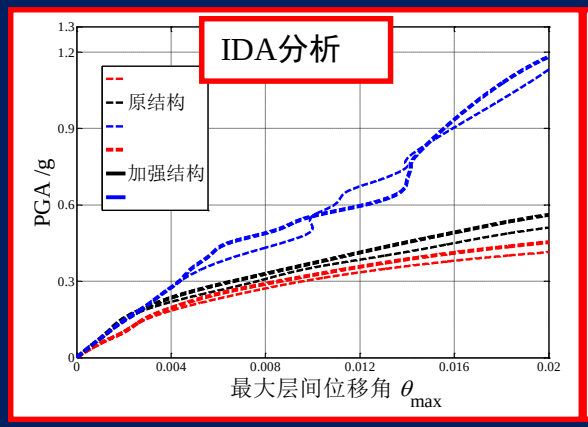
Seismic capacity corresponding to different modes 失效模式优化

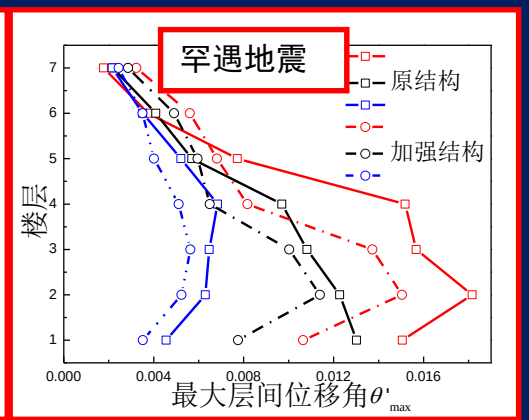
优化方案验证

- 静力非线性分析
- 非线性动力分析
- 工程成本分析







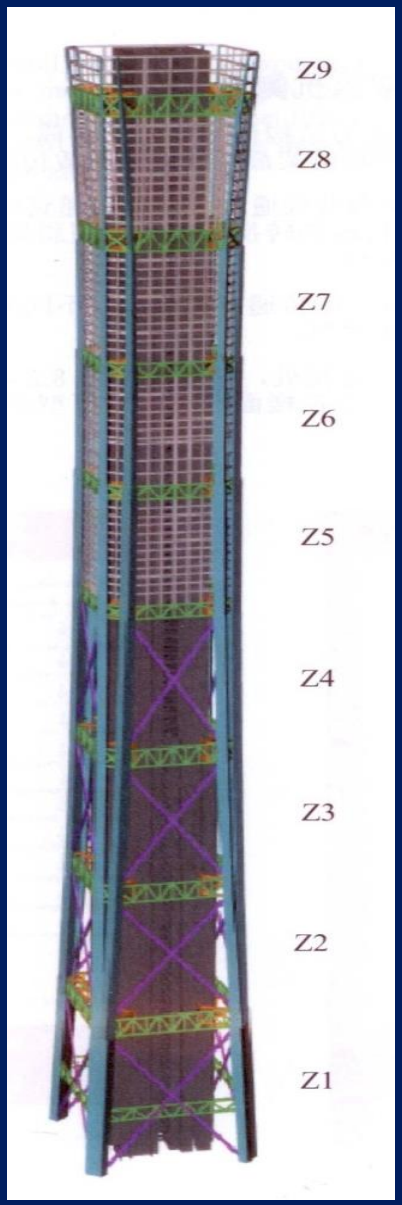


材料成本增加 2.4%
整体抗震能力提高约30%

优化方案能提高结构的整体抗震能力，表明所提优化方法的可行性和有效性

内部讲义，请勿扩散，版权归演讲者所有

5、大型结构灾变模拟的创新与集成



单元——单元划分

模型——单元及其耦合模型

算法——方程求解

准则——单元失效、退出准则，结构失效或倒塌准则

输入——强地震 / 强风场作用

数值模拟集成系统

内部讲义，请勿扩散，版权归演讲者所有

创新和集成应用平台：

自主的、比较成熟的大型结构数值模拟软件平台

集成创新的成果：

新单元——可更好模拟结构材料、块体或部件的新型独立单元，比方说：纤维单元、壳单元、离散单元等

新模型——材料本构模型（率相关）、构件的恢复力模型、流－固耦合模型、土－结等多介质耦合模型等

新算法——求解多维、非线性、强耦合等大型微分方程（负刚度、奇异性）等算法

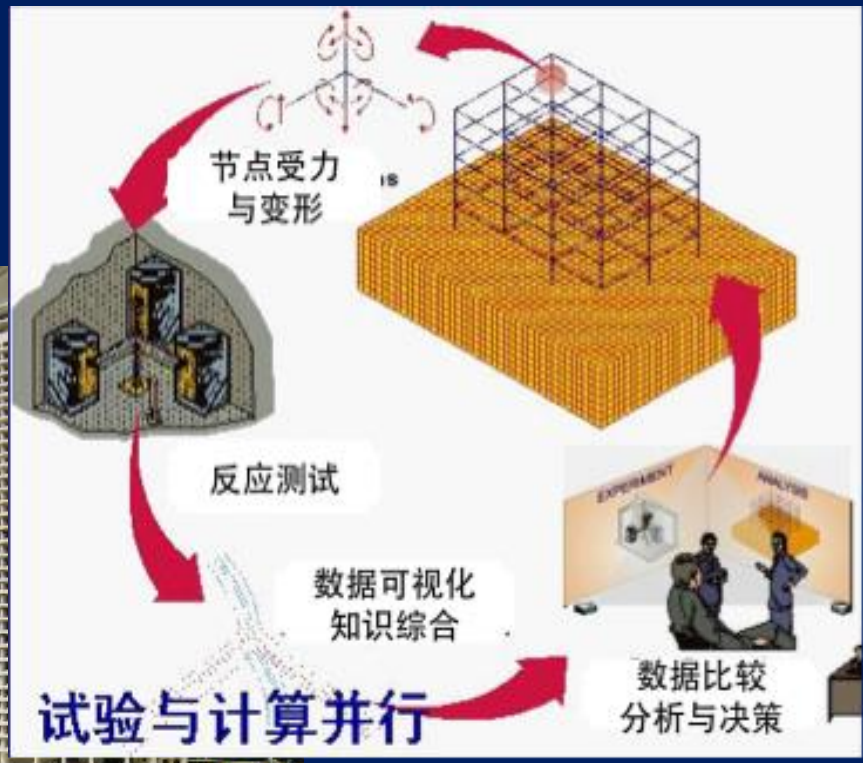
重大工程的动力灾变模拟与集成平台严重受制于别国软件的产权保护——没有自主的软件平台，创新成果无法集成用于大型结构地震灾变模拟！

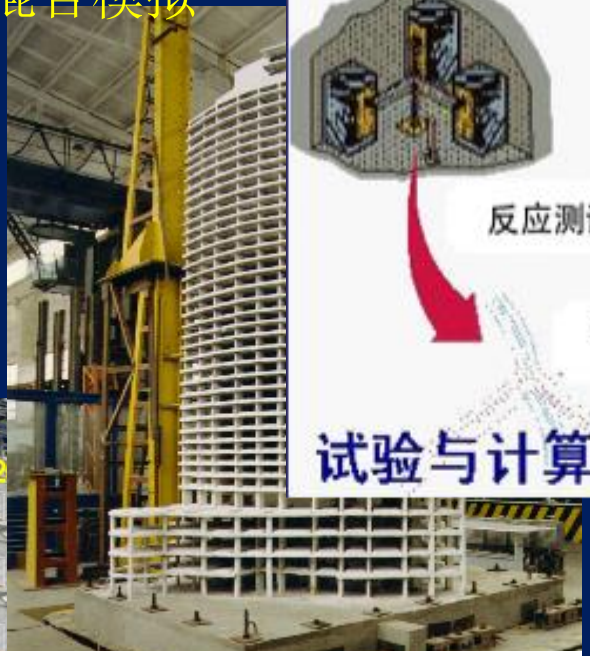
内部讲义，请勿扩散，版权归演讲者所有

6. Physical and numerical hybrid simulation for d和amage evolution and collapse of infrastructures

重大工程动力灾变过程的物理和混合模拟

- **Some issues：**





缩尺物理模型试验的相似性
模拟理论制约

足尺物理模型试验难以实现

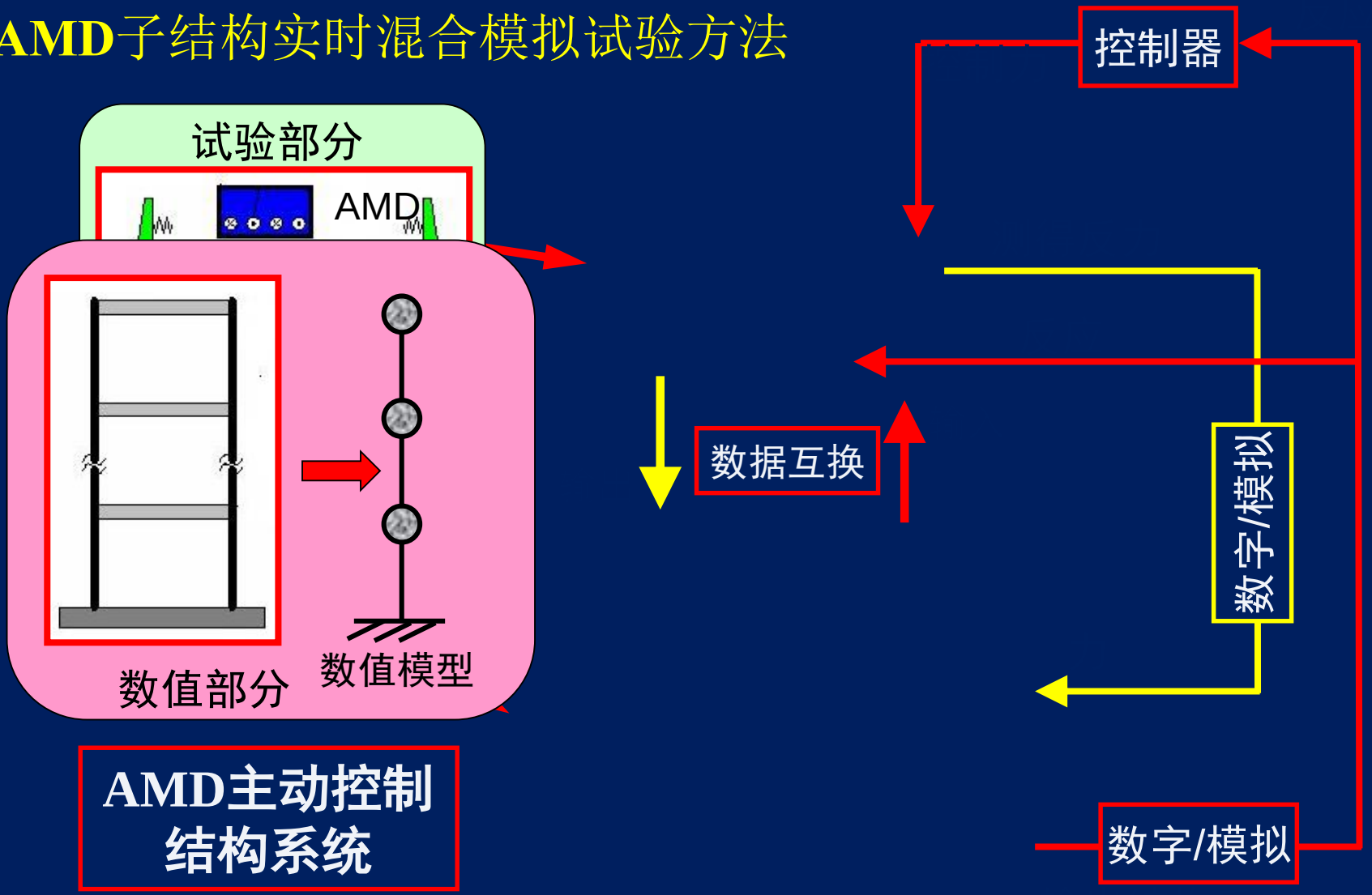
Solution: Real-time simulation of sub-structure physical tests combined with numerical analysis of whole structure (NEES)

前沿：子结构物理模型试验与数值计算并行实时模拟

内部讲义，请勿扩散，版权归演讲者所有

- AMD real-time hybrid-simulation

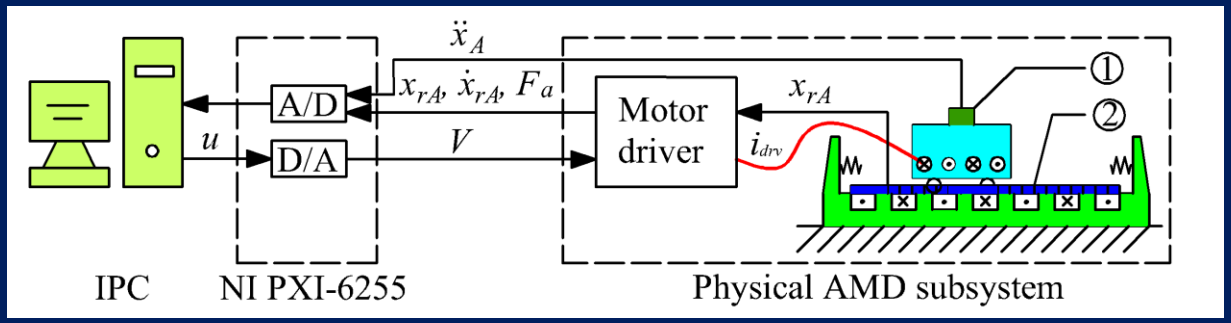
- AMD子结构实时混合模拟试验方法

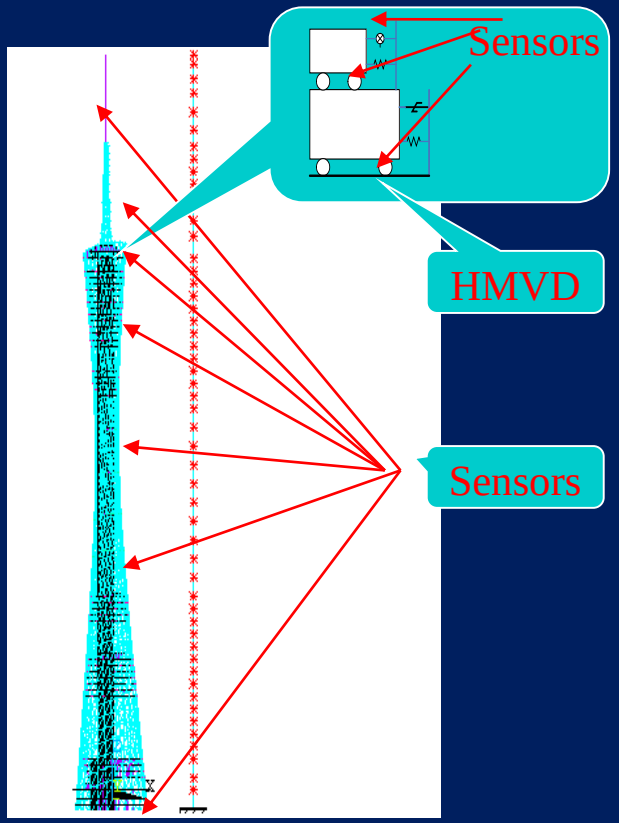


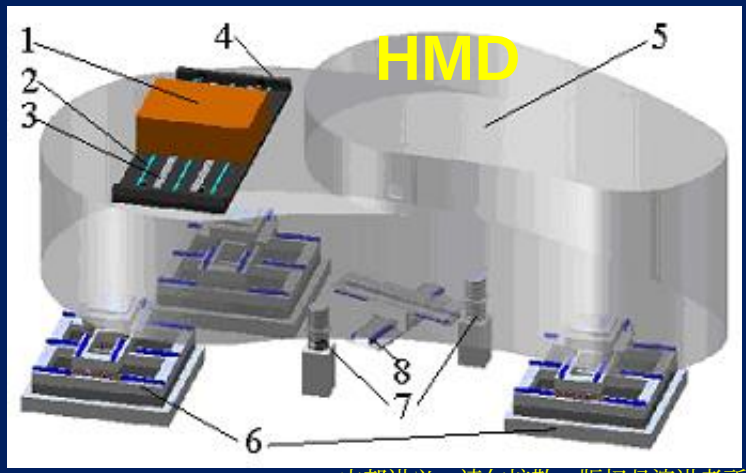
内部讲义，请勿扩散，版权归演讲者所有

- **Guangzhou TV Tower**

广州电视塔缩尺AMD子结构试验







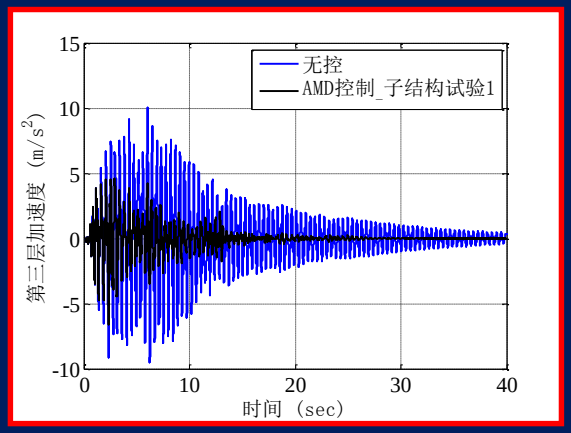
广州电视塔

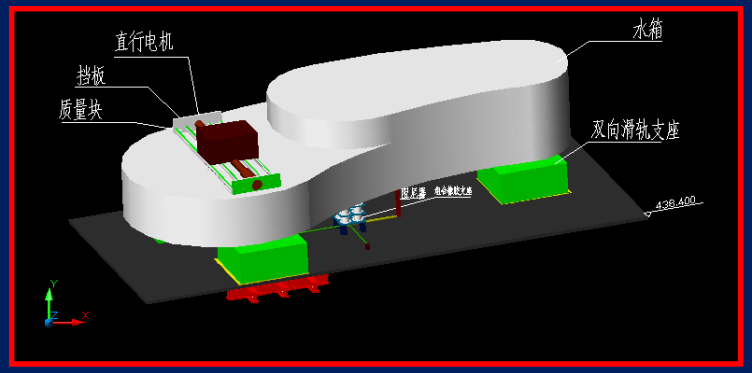
610m高=主塔454m +天线 156m

内部讲义，请勿扩散，版权归演讲者所有

AMD子结构试验与控制效果

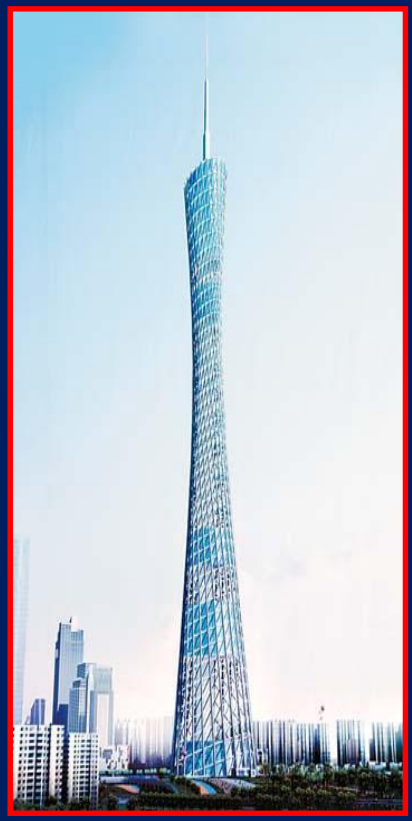
控制效果（结构第三层加速度）





AMD子系统实验结果

子系统实验结果与仿真结果比较



第一次在主动控制领域提出了振动控制系统的物理试验与数值模拟混合方法，能够有效检验足尺AMD主动控制结构振动的效果。

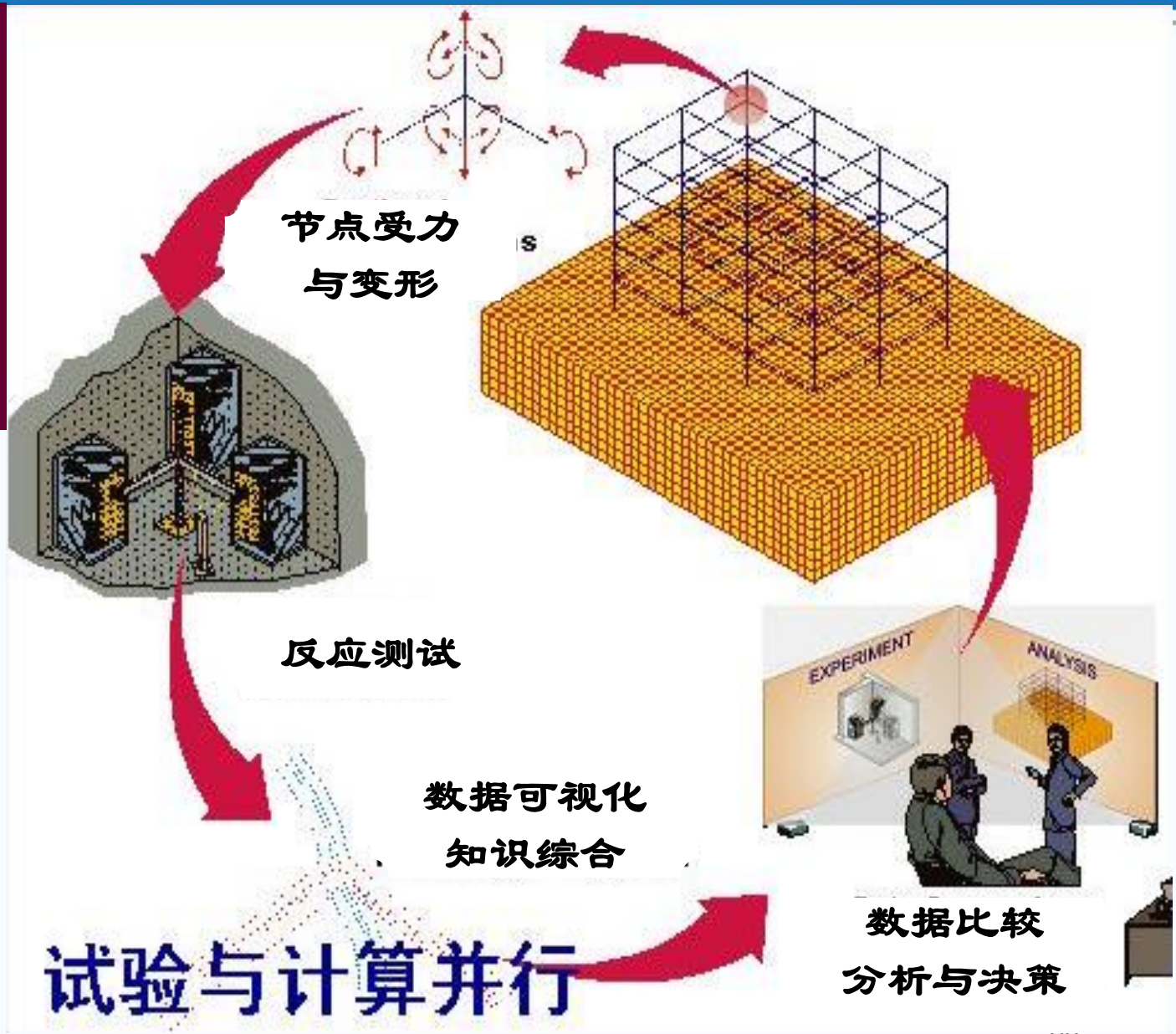
内部讲义，请勿扩散，版权归演讲者所有

混合模拟面临新的挑战

新的挑战：

1、大型结构子结构边界条件及其混合模拟实验装置

2、实时混合模拟的多作动器控制、时滞及其补偿



内部讲义，请勿扩散，版权归演讲者所有

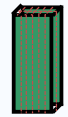
7）数值子结构方法

基本原理

u_{Test} F_{Test}

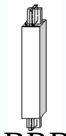
Hybrid testing substructure

$u_{BeamCol}$ $F_{BeamCol}$



Frame

u_{BRB} F_{BRB}

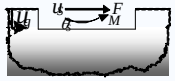


BRB

u_{Wall} F_{Wall}

Shear Wall

u_{Base} F_{Base}



Foundations and soils

大规模弹性主结构

小规模非线性精细化子结构

结构运动方程 ：

$$\mathbf{M}\ddot{\mathbf{U}}+\mathbf{C}\dot{\mathbf{U}}+\mathbf{R}+\mathbf{K}_g\mathbf{U}=\mathbf{F}$$

改进后方程：

$$\mathbf{M}\ddot{\mathbf{U}}+\mathbf{C}\dot{\mathbf{U}}+\mathbf{K}_m\mathbf{U}=\mathbf{F}+\tilde{\mathbf{F}}+\mathbf{F}_g$$

改进后方程离散 ：

$$\mathbf{K}^{\mathrm{dyn}}\mathbf{U}_{n+1}=\mathbf{P}_{n+1}+\tilde{\mathbf{F}}_{n+1}+\mathbf{F}_g^{n+1}$$

其中：

1) $\mathbf{K}^{\mathrm{dyn}}$ **常刚度项**

2) $\mathbf{P}_{n+1}$ **等效外荷载**

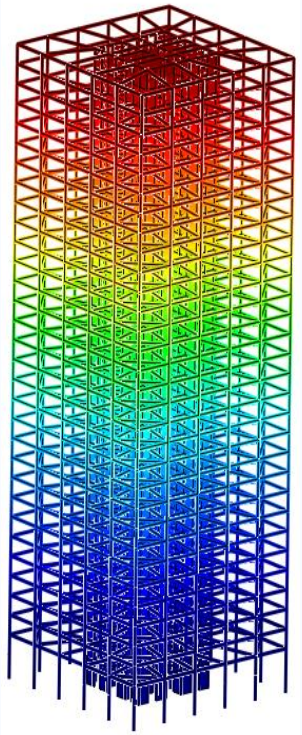
3) **材料非线性修正力** $\tilde{\mathbf{F}}_{n+1}=\mathbf{K}_m\mathbf{U}_{n+1}-\mathbf{R}(\mathbf{U}_{n+1})$

4) **几何非线性修正力** $\mathbf{F}_g^{n+1}=-\mathbf{K}_g\mathbf{U}_{n+1}$

内部讲义，请勿扩散，版权归演讲者所有

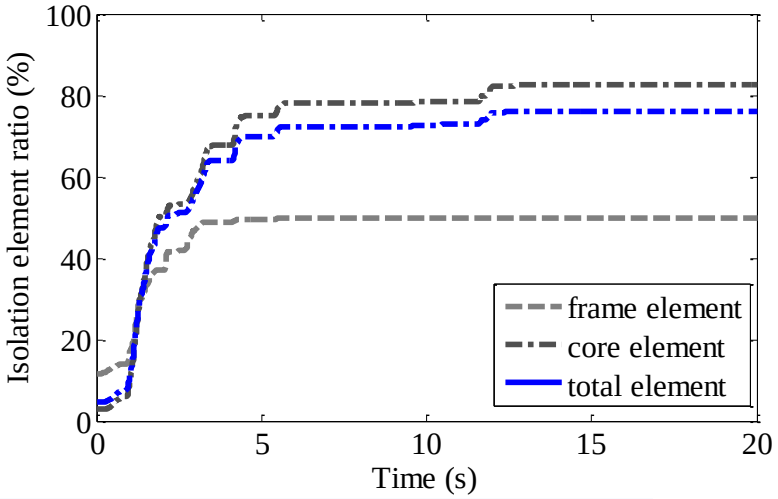
7）数值子结构方法

● 应用实例



高层RC框架-剪力墙

- **层数**：32
- **楼高**：129 **m**
- **节点**：1290
- **单元**：5696
- **DOFs**：11520

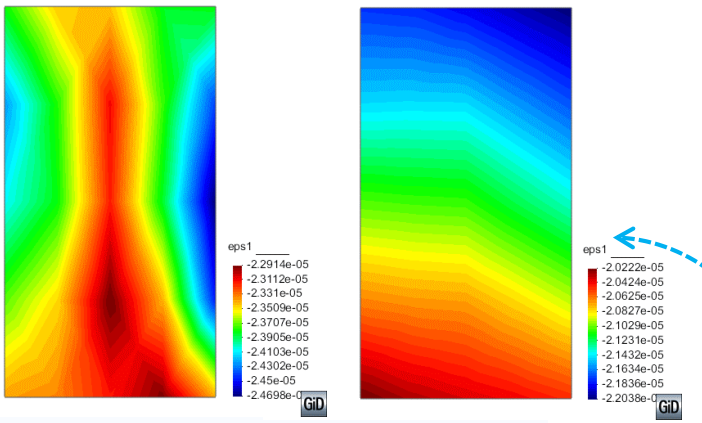


非线性子结构隔离数目时程曲线

√ 计算高效且准确

√ 实现局部精细化

√ 便于多尺度跨平台



典型剪力墙精细化子结构响应

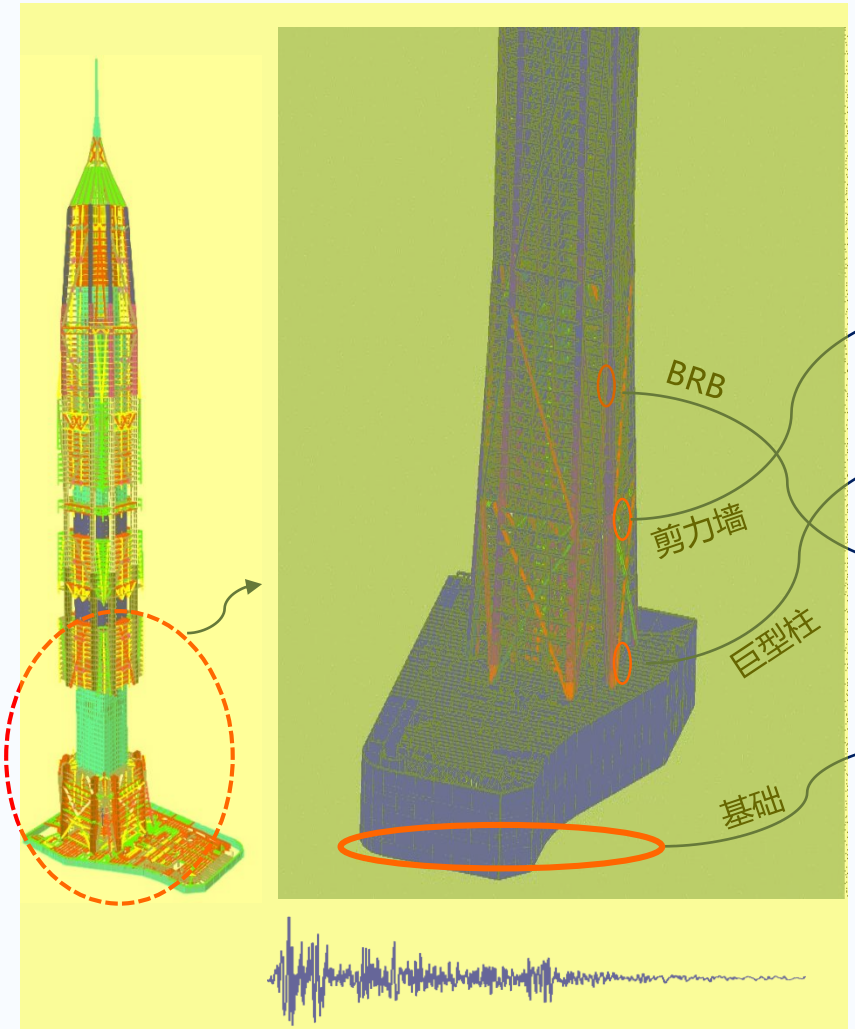
内部讲义，请勿扩散，版权归演讲者所有

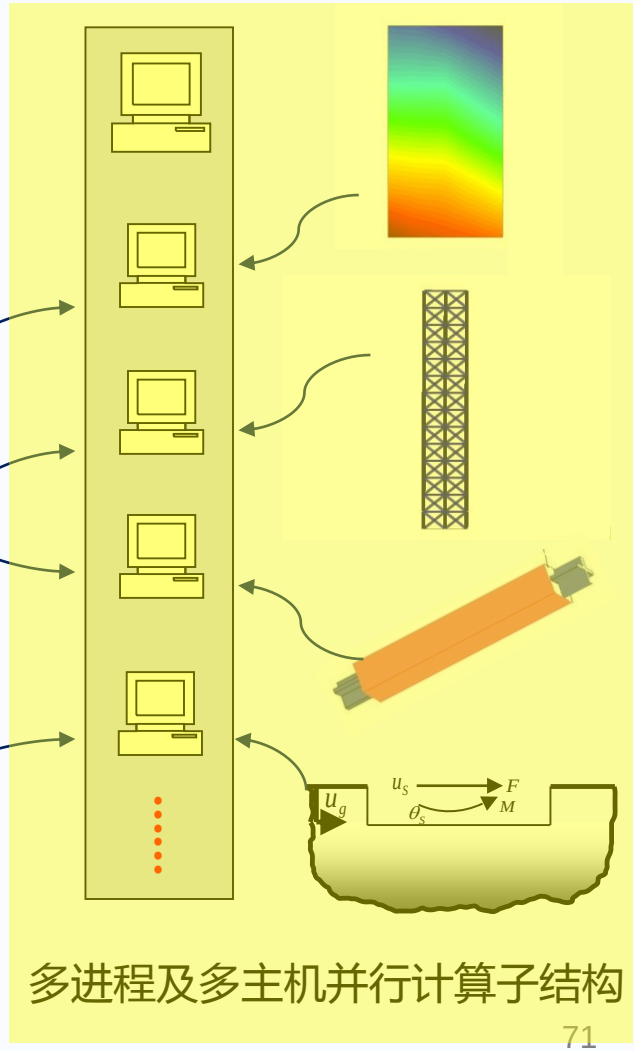
7）数值子结构方法

- 创新思路与要点

大规模线弹性主结构 ⟺ 反力与位移实时交互 ⟺ 不同的非线性精细化子结构模型

超高层结构





多进程及多主机并行计算子结构

内部讲义，请勿扩散，版权归演讲者所有

重大工程动力灾变
核心突破和相关成果

近场强地震动场
——经验模型；
理论模拟

近地台风/强风场
——工程化模拟、
经验模型

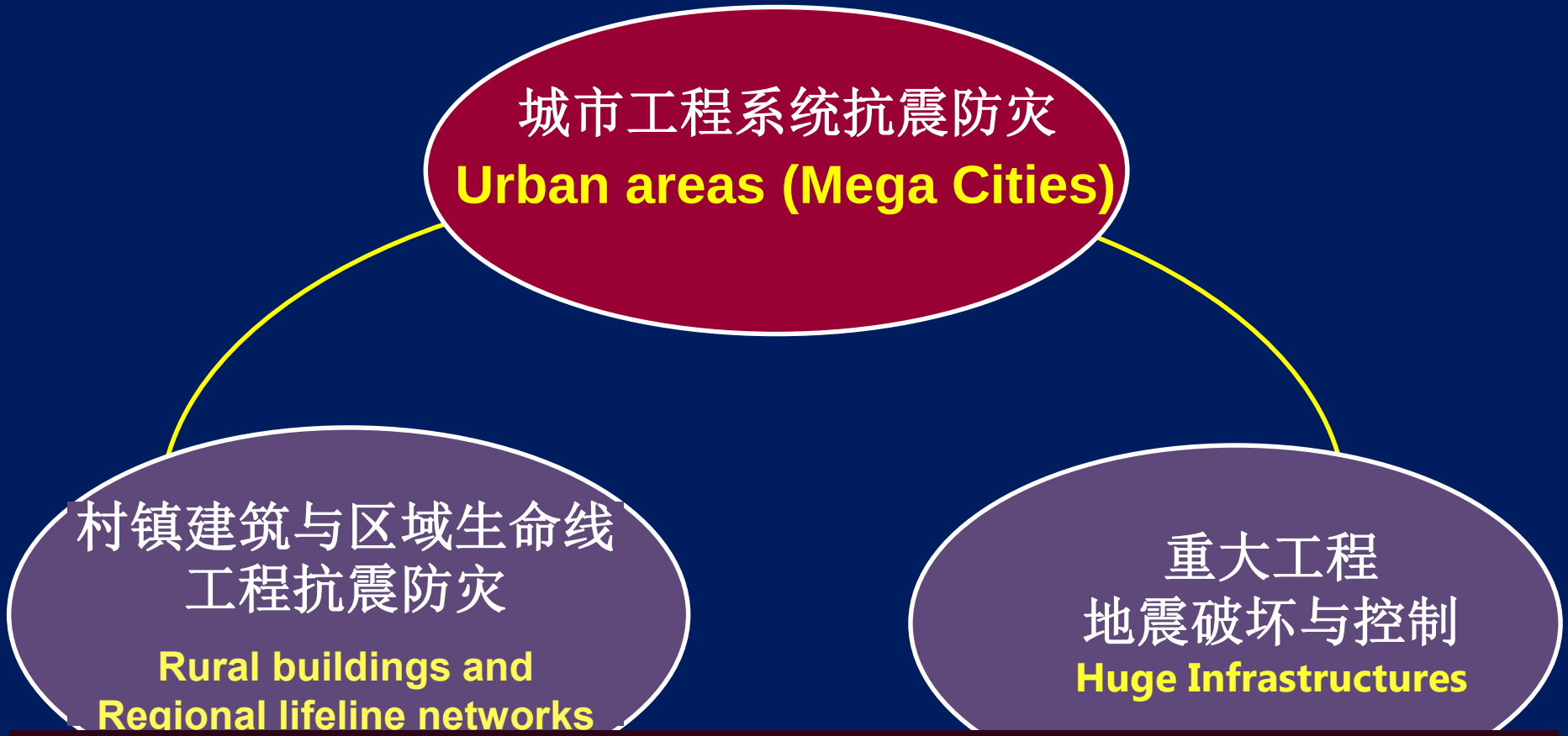
重大工程动力灾变
(损伤、破坏、倒塌)
演化过程、特征、机理

大型模拟平台
——计算软件，
混合模拟方法

重大工程灾变模拟
验证与应用
——震害验证、监测
验证、重大工程应用

内部讲义，请勿扩散，版权归演讲者所有

中国工程抗震的三大领域
Main Issues of Earthquake Engineering in China



机遇与挑战，任重道远！

内部讲义，请勿扩散，版权归演讲者所有

Thanks!

谢谢！

内部讲义，请勿扩散，版权归演讲者所有