Seismic Safety for Hydropower Engineering in China

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Water and energy and the affected environment are key factors constrain the economic development and environmental improvement of China.

Based on the scenario studies, in the coming 20 years the demand of energy will double over the year 2000.

The energy consumption in China relies basically on coal, about 77% of the whole country. ***The terrible environmental problems are caused by direct combustion of coal.*** **At present China has been searching for the alternative energy supplies with the aim to reduce the share of coal.**

Up to now *wind power, solar energy, geothermal, biogas and wave energy* **are only the auxiliary energy resources because of the limitation for geographic, economic and technical reasons.**

Hydropower, **as a renewable and clean energy, with its potential ranked the world's first, plays an important role for sustainable development of energy and assure environment's security in China.**

The abundant hydropower, about 80% of the national total, is a superior resource in the developing region of the *Western China*. But its utilization ratio is very low, only less than 10% has been used.

To pursue sustainable, rapid and healthy development and to speed up the development in the Western region are the basic and macro strategies of economical development of Chinese government.

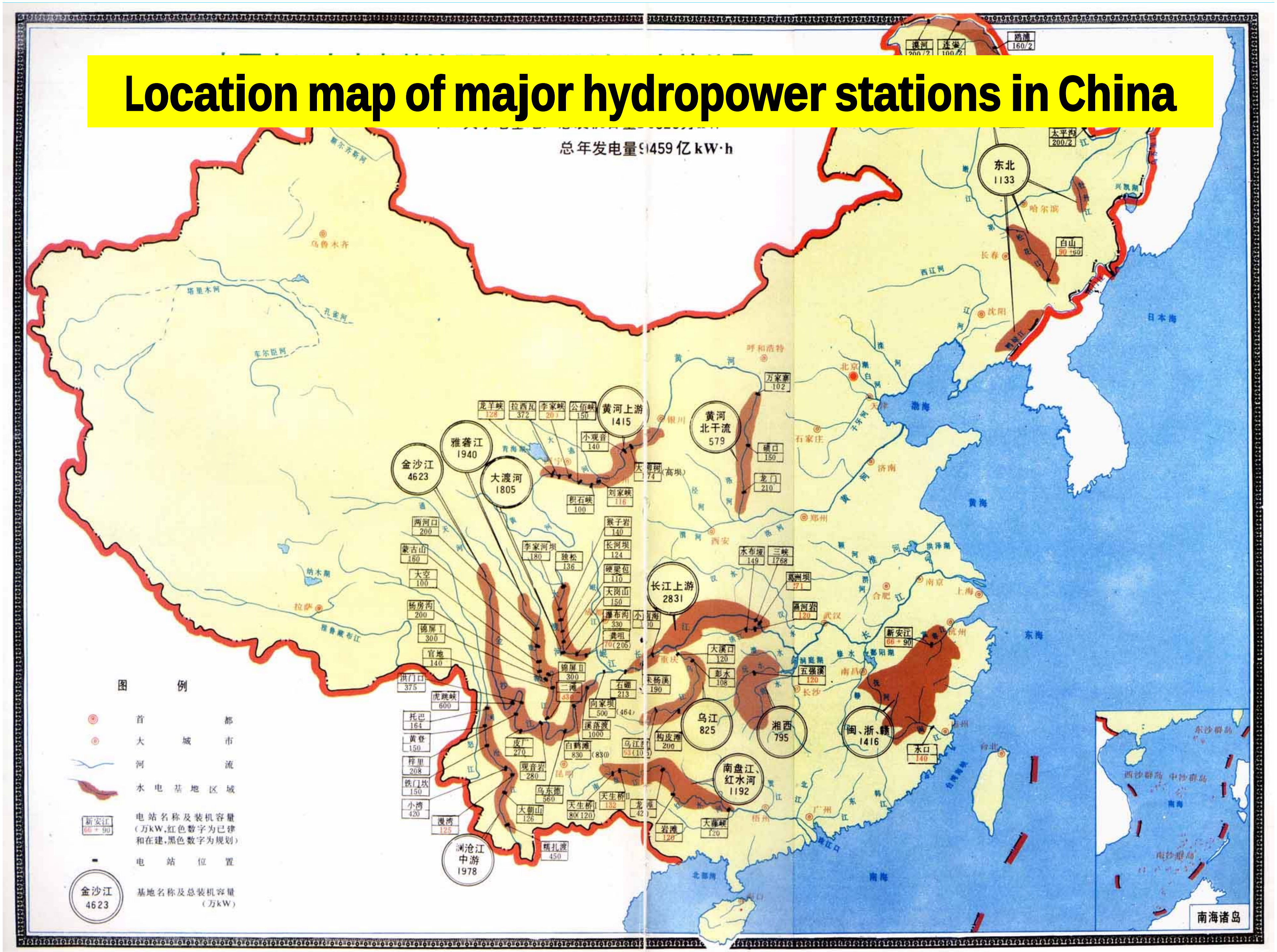
The rapid and sustainable hydropower development becomes critical not only for *providing safe and clean energy* ***to meet the increasing demand for electricity to power economic progress of the country, but also for*** *eradicating poverty* ***in this region.***

Many dam sites with geology and topography suitable for high dam with excellent regulating reservoir but only a small amount of resettlement are in this region.

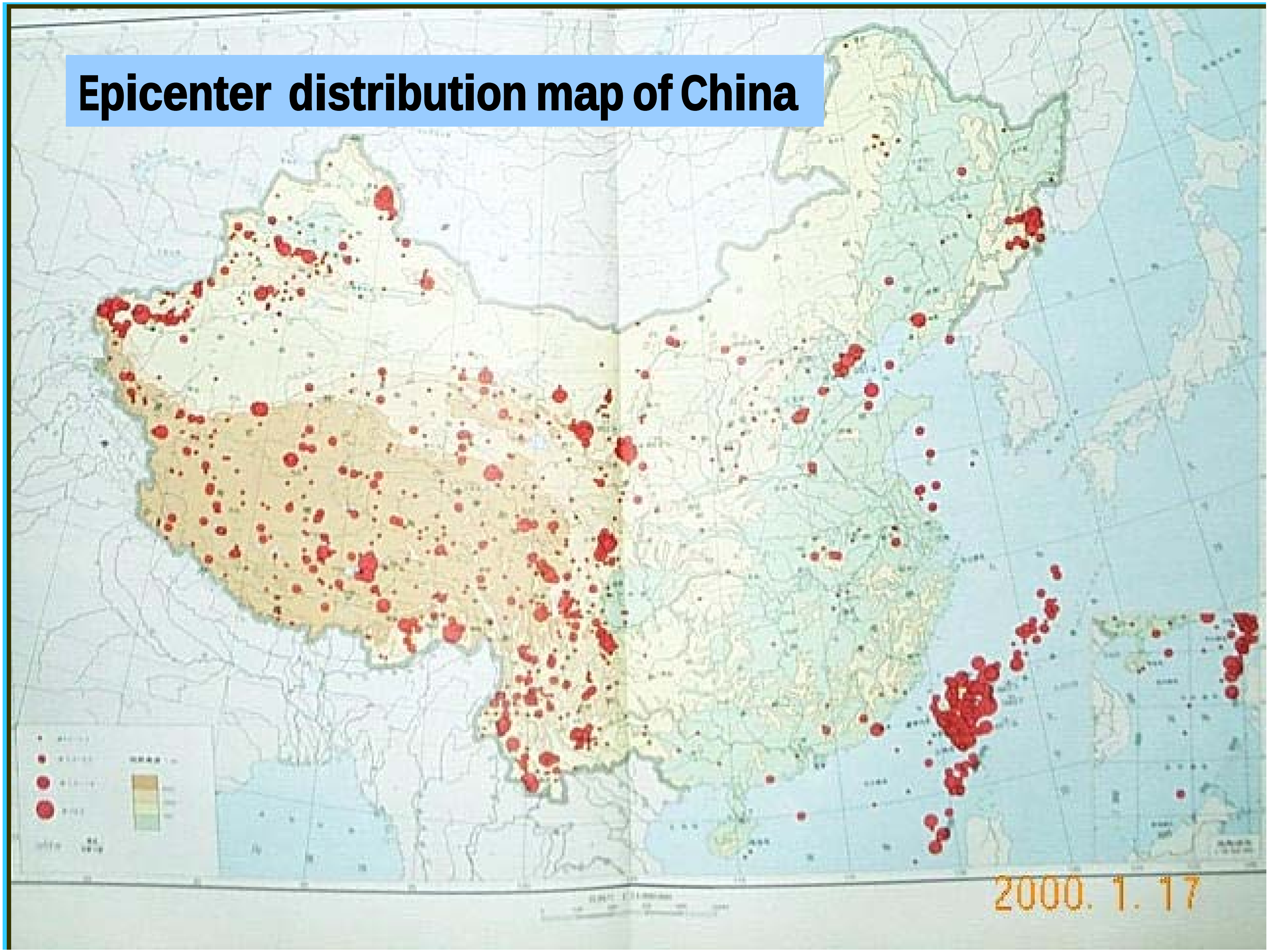
***However, this region is also well known for its high seismicty and frequent occurrence*.**

According to the statistics of the China Earthquake Administration, 82% of the strong earthquakes occurred in modern times in China were concentrated in this region.

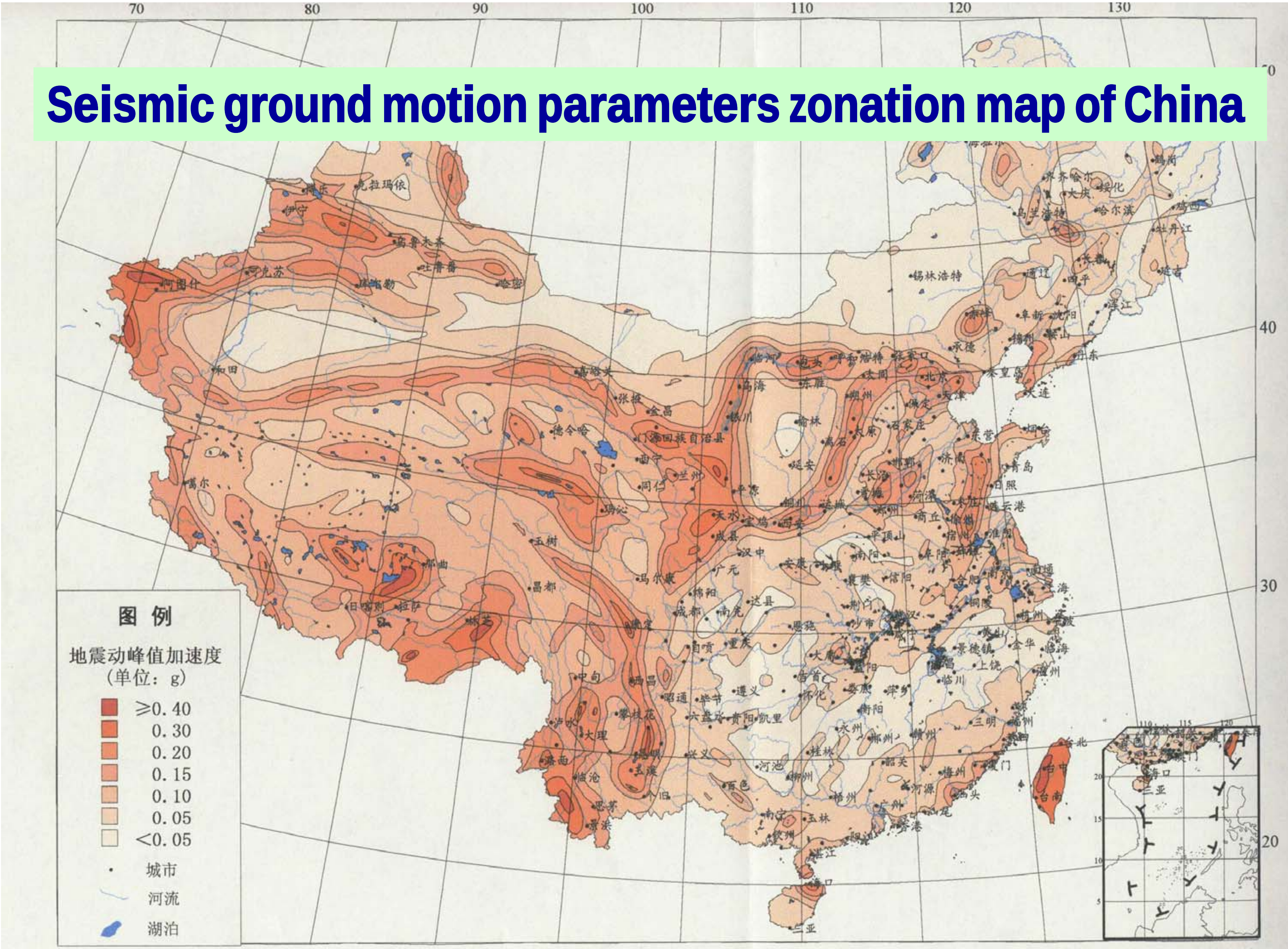
Location map of major hydropower stations in China



Epicenter distribution map of China



Seismic ground motion parameters zonation map of China



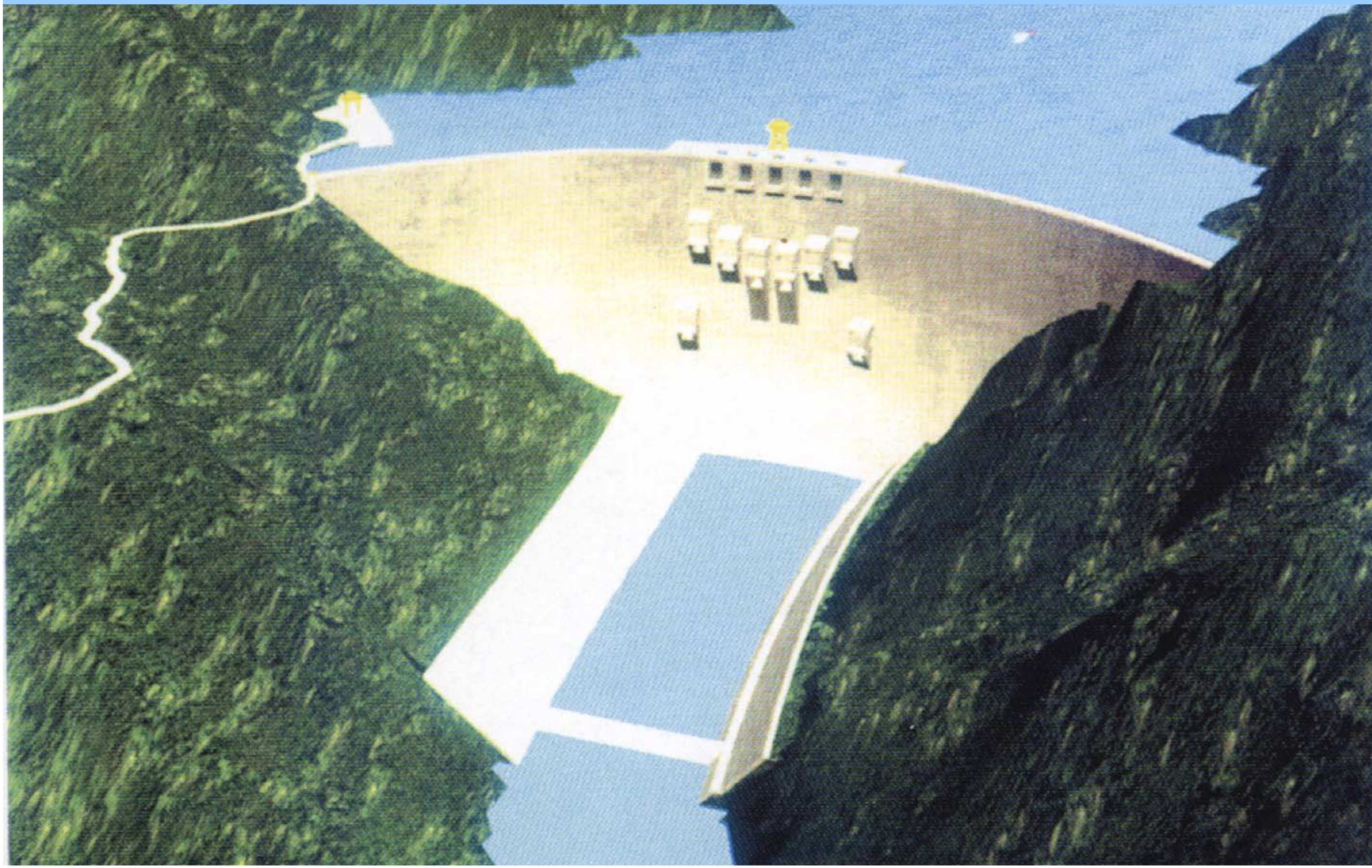
(注：本图是1:400万原图的示意图，征求意见用)

Many huge dams with rather high design acceleration (a_g) are located in this region

Jinping-I	**(H=305m,a_g=0.197g)**
Ertan	**(H=240m,a_g=0.20g)**
Longxiangxia	**(H=178m,a_g=0.23g)**
Xiaowan	**(H=292m,a_g=0.308g)**
Xiluodu	**(H=273m,a_g=0.321g)**
Baihetan	**(H=275m,a_g=0.325g)**
Hutiaoxia	**(H=278m,a_g=0.408g)**
Dagangshan	**(H=210m, a_g=0.542g)**

As all those are arch dams, the attention will be focused on the seismic safety of arch dams.

Xiaowan arch dam with a height of 292m located in area of high seismicity is now under construction and will be the world's highest arch dam



The problem of seismic phenomena is also associated with impounding of reservoir and is addressed as Reservoir Triggered Seismicity (RTS).

This problem has been seriously considered in dam engineering circles due to its environmental impact and risk consideration .

Among about 120 events of recognized RTS in 29 countries, 22 events occurred in China

As any accident of serious damage of high dam with huge reservoir during strong earthquake can inflict grave secondary catastrophe upon surrounding communities, the *seismic safety* of large hydropower project with high dam is naturally deeply concerned by our government and society.

Facing a *particular challenges* in this key technical problem of hydropower development in China, an extensive research on seismic design of high dam has been carried out in recent years.

A series of new conceptive progresses in seismic design of high dams have been initiated

In order to evaluate the seismic safety of a dam,

the input ground motion at dam site,
the method for analyzing seismic action effects of dam
the dynamic resistances of dam concrete

are the three main factors which should be consistent with each other.

Some latest advances in seismic research and design of high arch dams in China are briefly introduced as fellows:

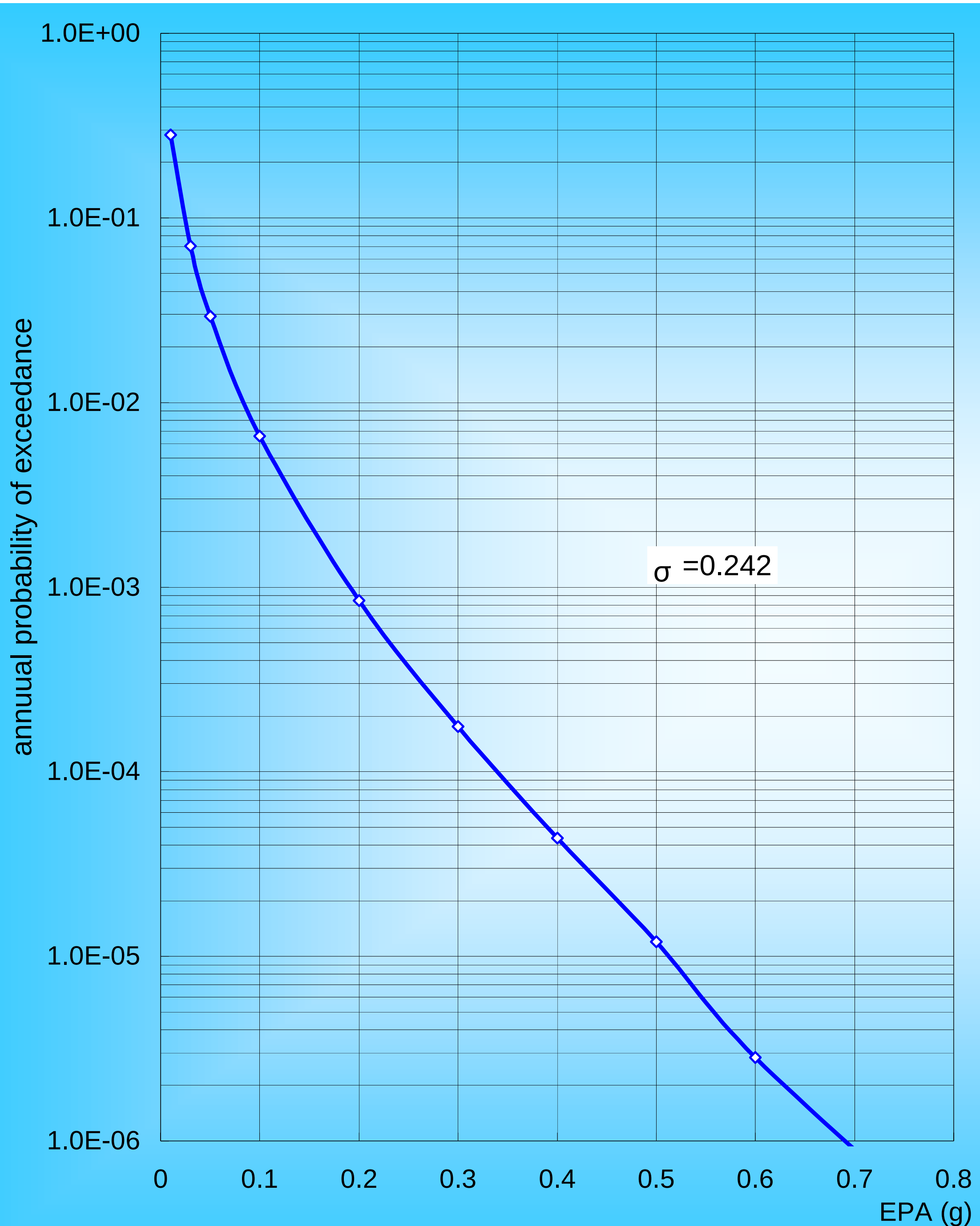
1. Site-specific input ground motion

- **Instead of the current peak ground acceleration (PGA), the spectrum related effective peak acceleration (EPA) is used in the seismic hazard evaluation of dam site.**

Based on the analysis of 145 accelerograms recorded at rock site in the Western United State, the *EPA* is defined as the spectral acceleration at period of 0.2 second divided by an average amplification factor of 2.5.

An *attenuation relationship for EPA* on the basis of regression model of *Abrahamson* was derived.

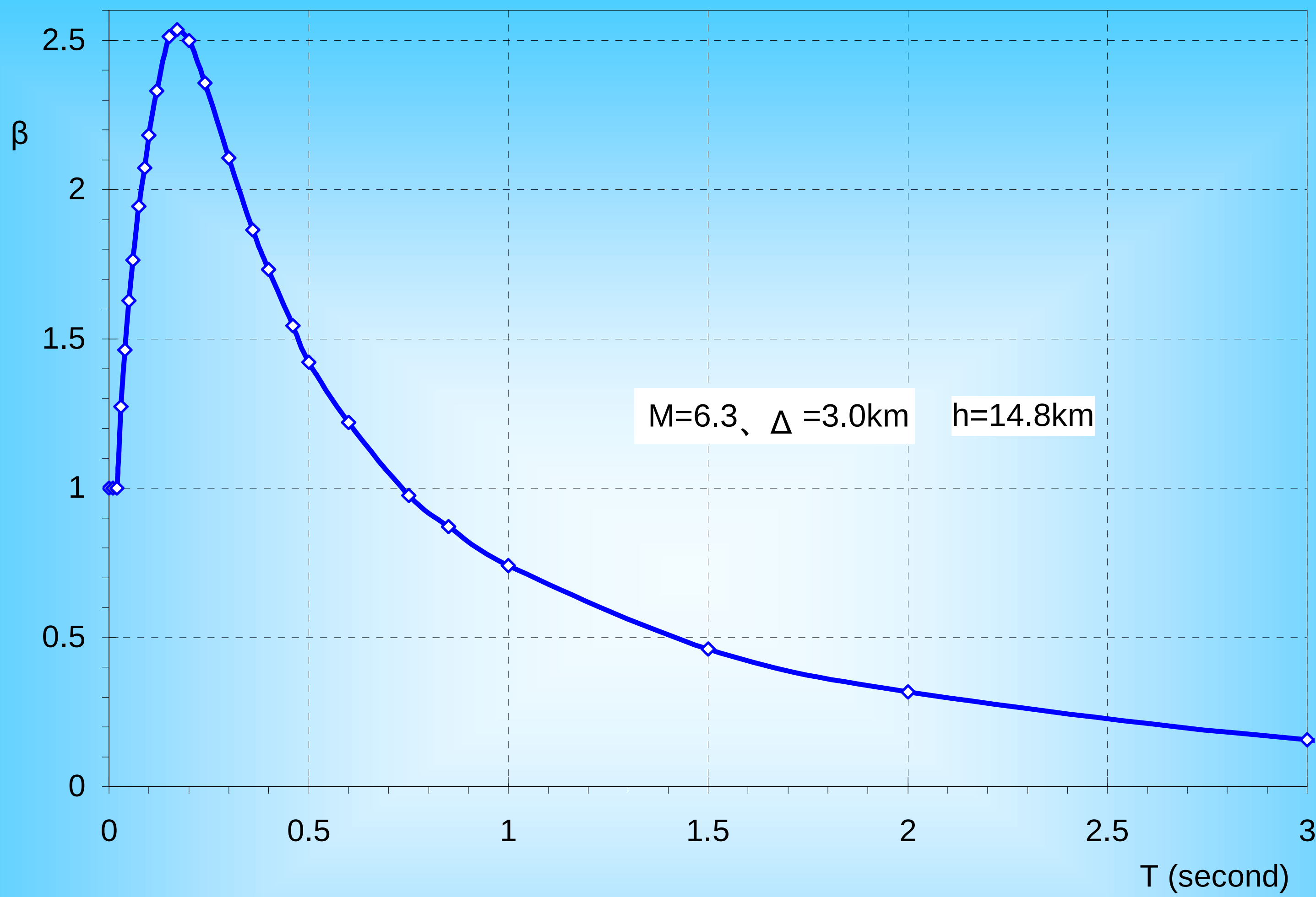
The hazard curve of *EPA* can be obtained from seismic hazard evaluation at dam site.



Hazard curve of *EPA* from seismic hazard evaluation for Xiaowan arch dam

- **Also, the widely used "*equal-hazard spectrum*" has been replaced by a hybrid method combining both probabilistic and deterministic approaches of selecting *specific scenario earthquake* with maximum probability and consistent with the design *EPA* at dam site.**

A more realistic "*site-specific design spectrum*" with definite probability of exceedance can be determined from the selected scenario earthquake



Site-specific design spectrum **with definite probability of exceedance determined from the selected scenario earthquake for Xiaowan arch dam**

- **A framework of performance-based seismic design with dual fortification earthquake levels of *MDE* (*Maximum Design Earthquake*) and *MCE*(*Maximum Credible Earthquake*) has been established to substitute for traditional dual levels of *OBE* (*Operating Basis Earthquake*)and *MCE*.**

The MCE can be determined definitely as a special kind of scenario earthquake with the upper limit magnitude and the shortest possible distance to dam site within the seismic source zone of maximum contribution.

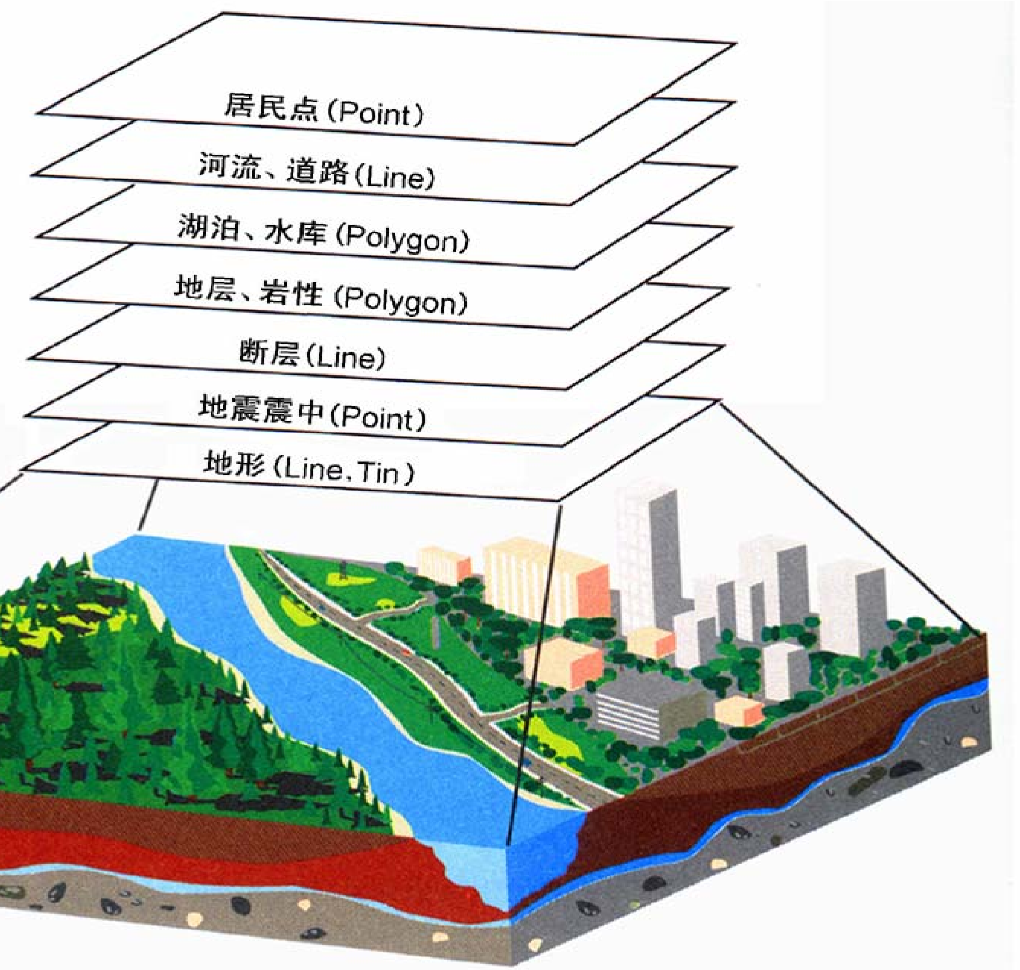
• **A more systematic and effective procedure for** ***Reservoir Triggered Seismicity (RTS)*** **has formed and widely used in practice in China.**

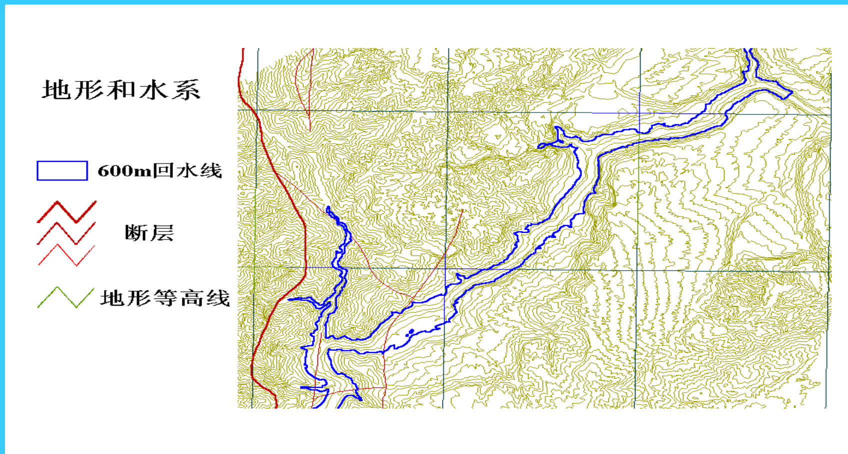
The digital seismic monitoring of ***RTS*** **and strong motion observation have been implemented in many hydropower projects.**

A digital monitoring system with 22 fixed and 8 movable stations has been in operation for the Three Georges Project before impounding of its reservoir.

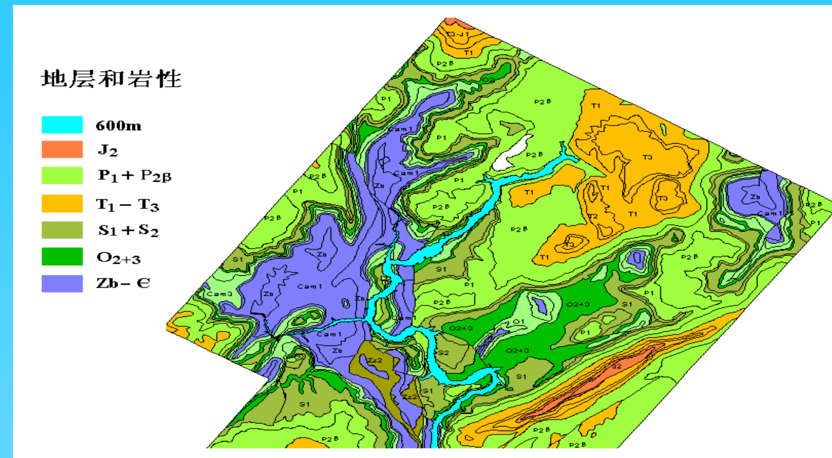
The study on RTS by using Geological Information System (GIS) has been achieved.

Themes:

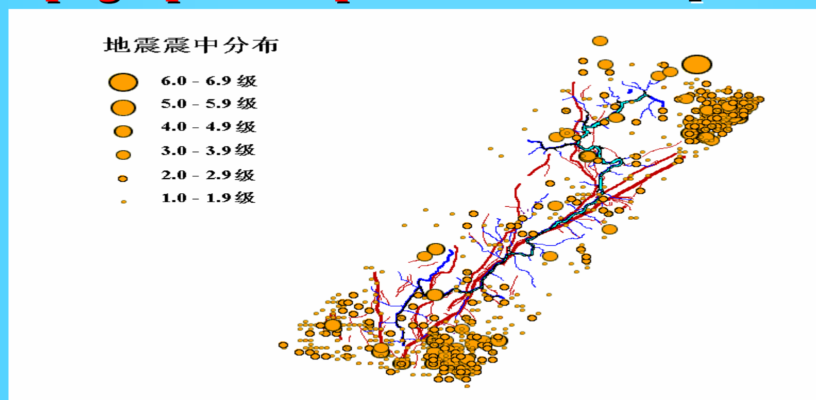




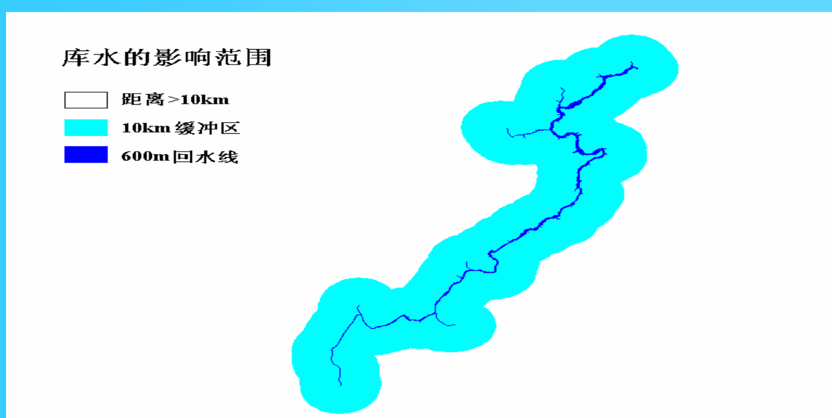
Input data 1:Topographic Map



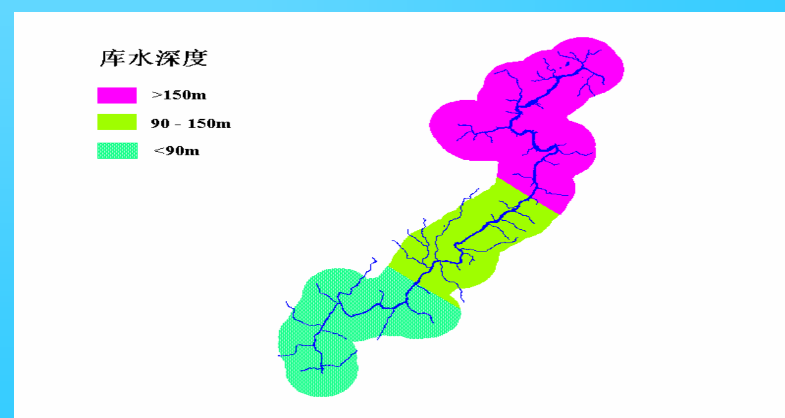
Input data 2:Geologic Map



Input data 3:
Epicenter

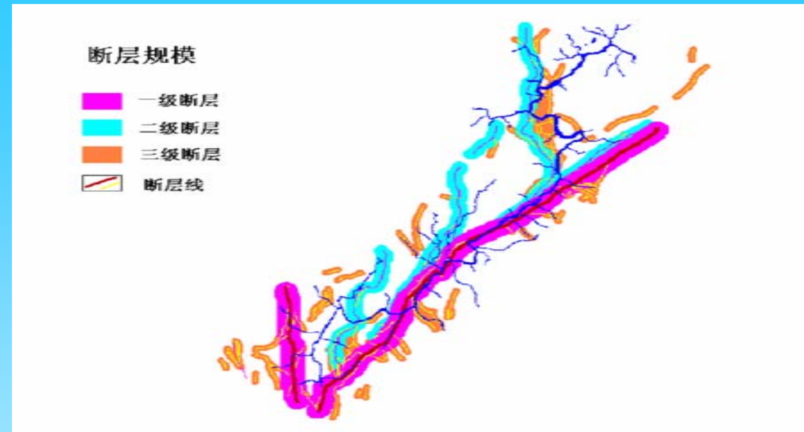


Influence Factors 1: Connection with reservoir

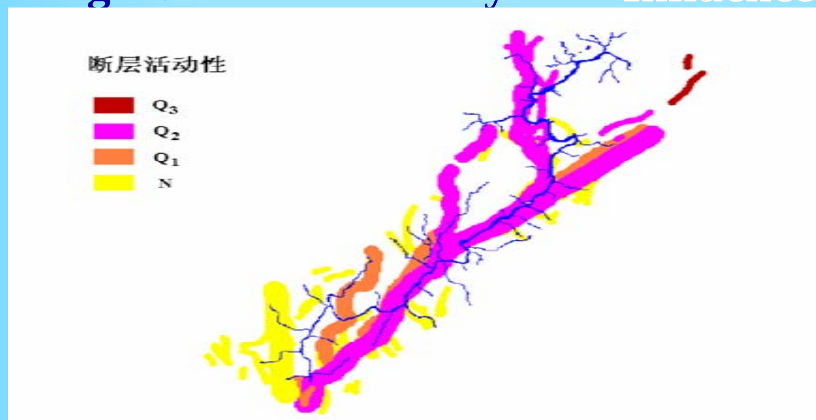


Influence Factors 2:Depth of water

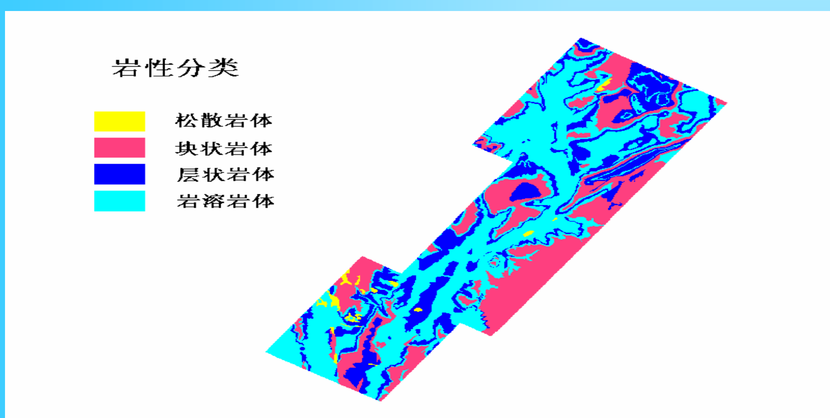
Influence Factors 3:Background of Seismicity



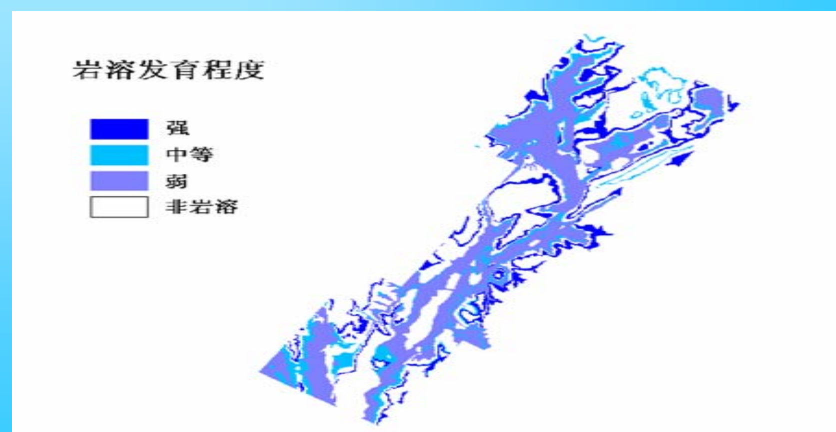
Influence Factors 4:Scale of faults



Influence Factors 5: Activity of faults

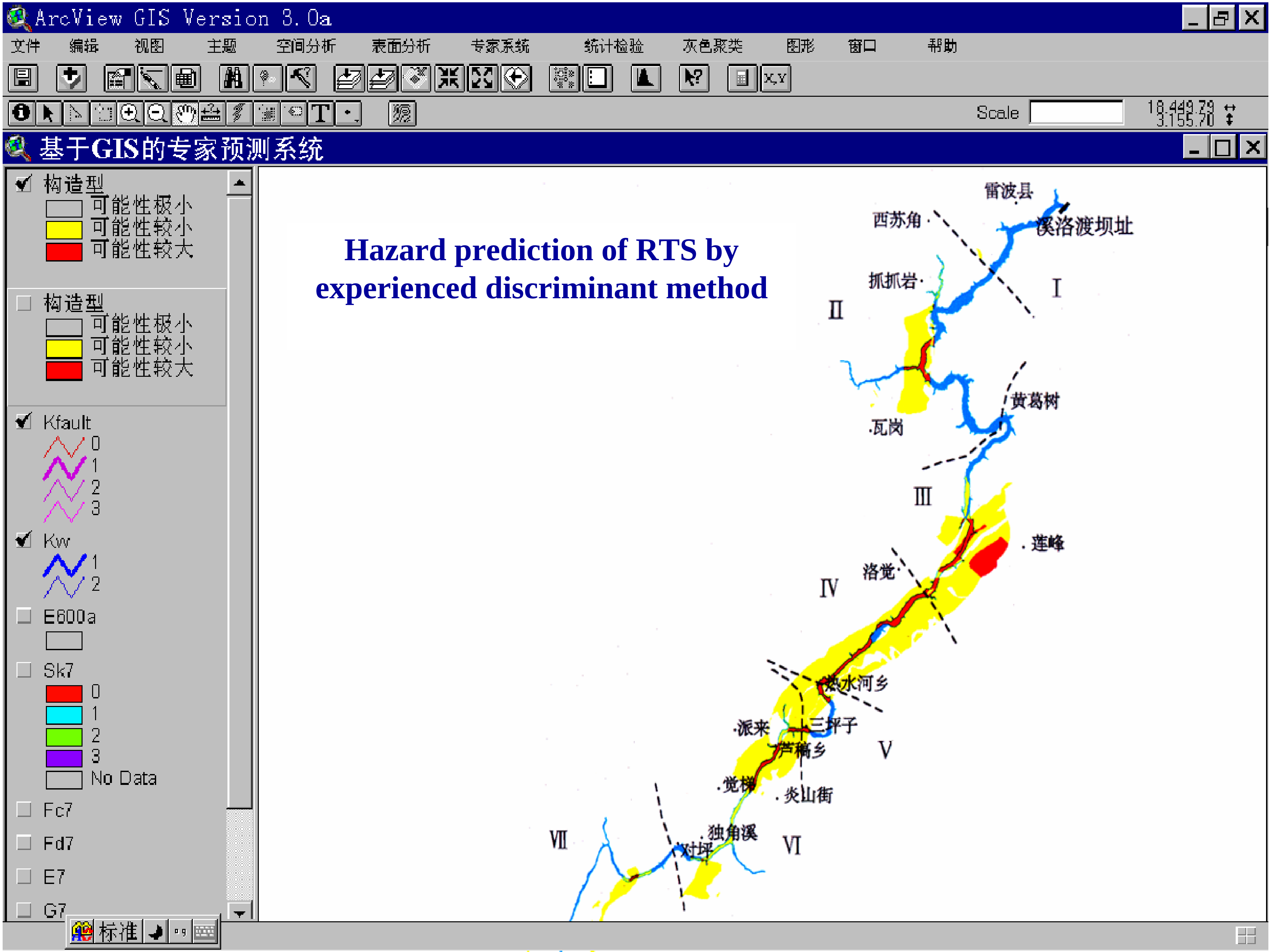


Influence Factors 6:Property of rockmass



Influence Factors 7: Level of karst developing

Hazard prediction of RTS by experienced discriminant method



2. Seismic action effects of dams

- **Recently, great efforts have been made in analyzing the seismic action effects of arch dams.**

  A more realistic model and effective numerical method with consideration of all the following critical problems simultaneously has been developed and widely used in China.

1. *Opening of contraction joints within dam during strong earthquake;*

2. *Radiation damping of energy dispersion in far-field foundation;*

3. *Topography features and geological disturbances including all potential sliding blocks of arch dam abutments at both banks within the near-field foundation adjacent to dam;*

4. *Dynamic interaction of dam-foundation-reservoir;*

5. *Spatial variation of seismic input along dam foundation.*

In this model:

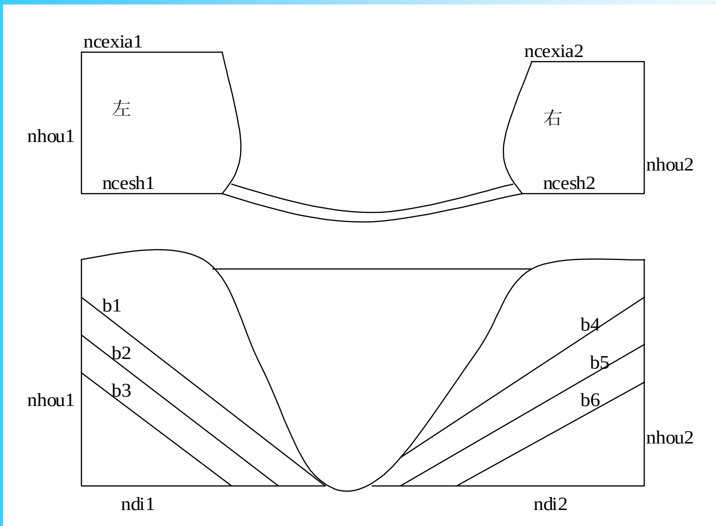
The far-field foundation region is replaced by a set of artificial *transmitting boundaries*.

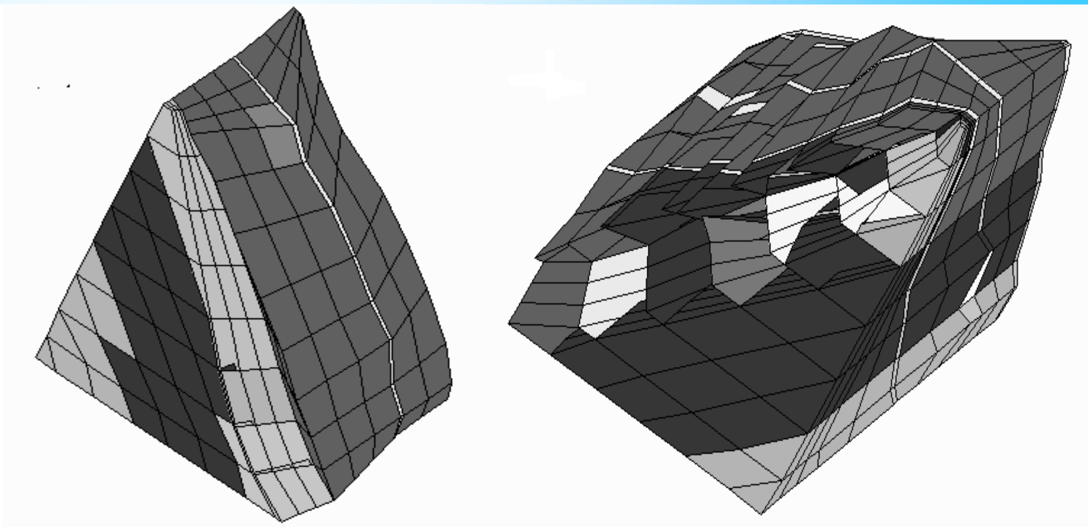
Both contraction joints within dam and all boundary interfaces of abutment sliding blocks are treated on basis of *dynamic contact theory with friction and cohesion*.

Also, *a contact joint is set along the dam-foundation interface but with the initial strength of dam concrete*.

The effects of local opening and slipping of all joints can be taken into account.

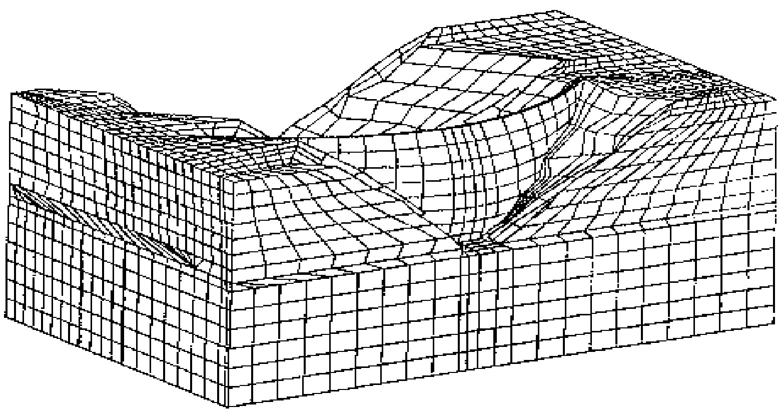
Three potential blocks of the foundation rock at abutments of each canyon bank determined by the geologic engineers for *Xiaowan arch dam*.

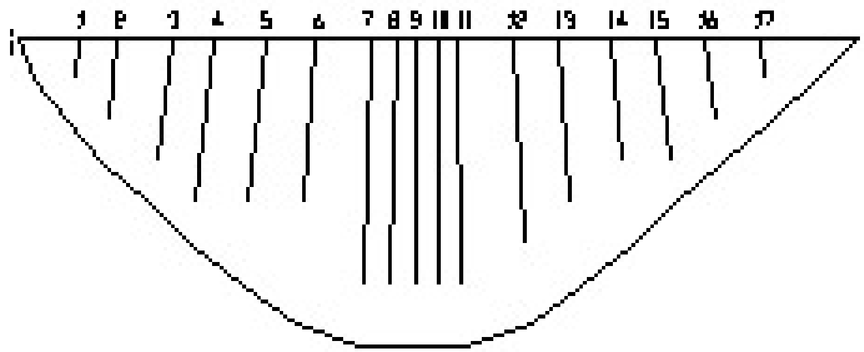




The model of the whole system is discrete in space by finite elements and in time by central finite-differences.

Its equation of motion is solved as a wave propagation problem by explicit integration in time domain .





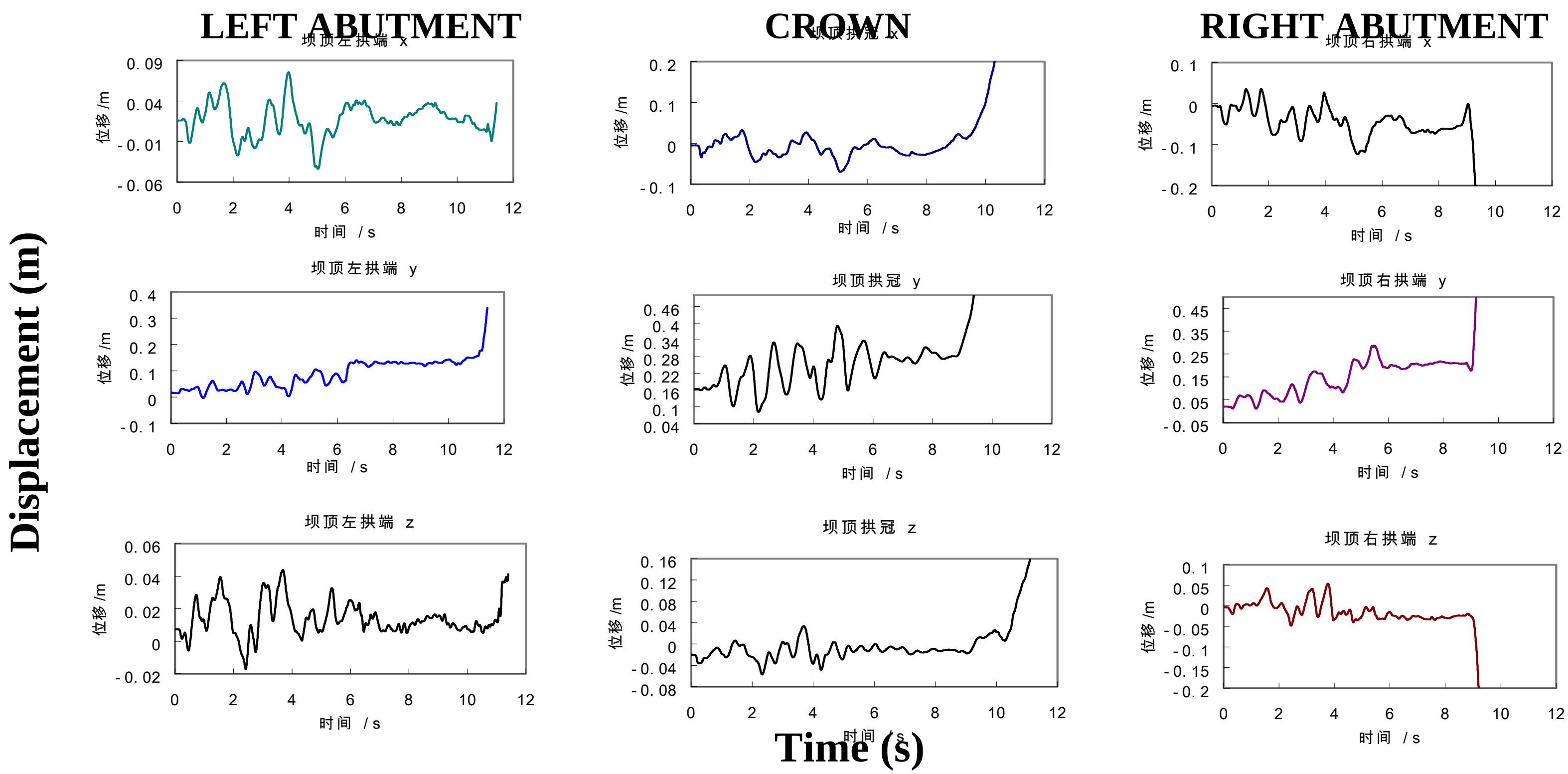
The discrete mesh of the Xiaowan arch dam system, in which the mesh of the transmitting boundaries is hidden. In this model 17 more critical contraction joints are taken into account.

• **The performance objective of limited local reparable damage for *MDE* is realized by ensuring *the total main principal stresses in dam under the combination of static loads and the MDE within its dynamic strength capacity of dam concrete.***

However, the limit state of uncontrolled release water from reservoir for *MCE* should be identified by *dynamic instability of the integrated dam-foundation system.*

• The *traditional approach* used for stability analysis of arch dam abutment blocks is essentially a time-independent static method without consideration of the dynamic deformation coupling between the dam and foundation. *It causes the results far from the real dynamic stability behavior of the integrated dam-foundation-reservoir system during strong earthquake.*

From engineering point of view, *a new conception from the abrupt junction of displacement responses* of the system during earthquake as its criterion of stability assessment is suggested.



Instable time histories of the displacement responses of dam at crown and abutments at crest for the ultimate earthquake with an EPA of 540 gal

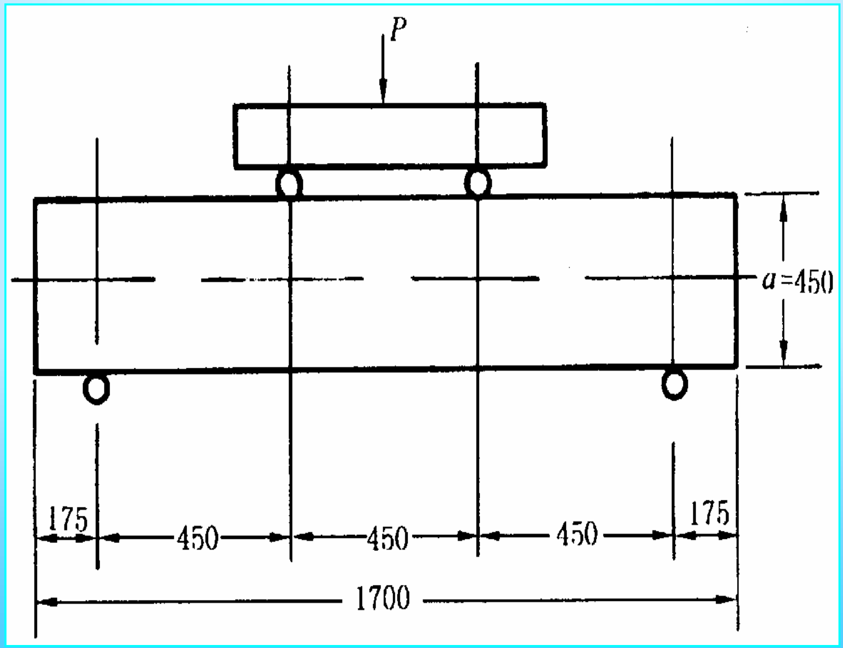
The ratio of the seismic action caused the limit state with abrupt junction of displacement responses to that of MDE provided a so-called overload safety factor. The damage criterion for MCE can be defined as with a overload safety factor no less than 1.0.

3. Dynamic behavior of dam concrete

Dam concrete is distinct from ordinary concrete for its more heterogeneous of mixing multi-graded aggregates.

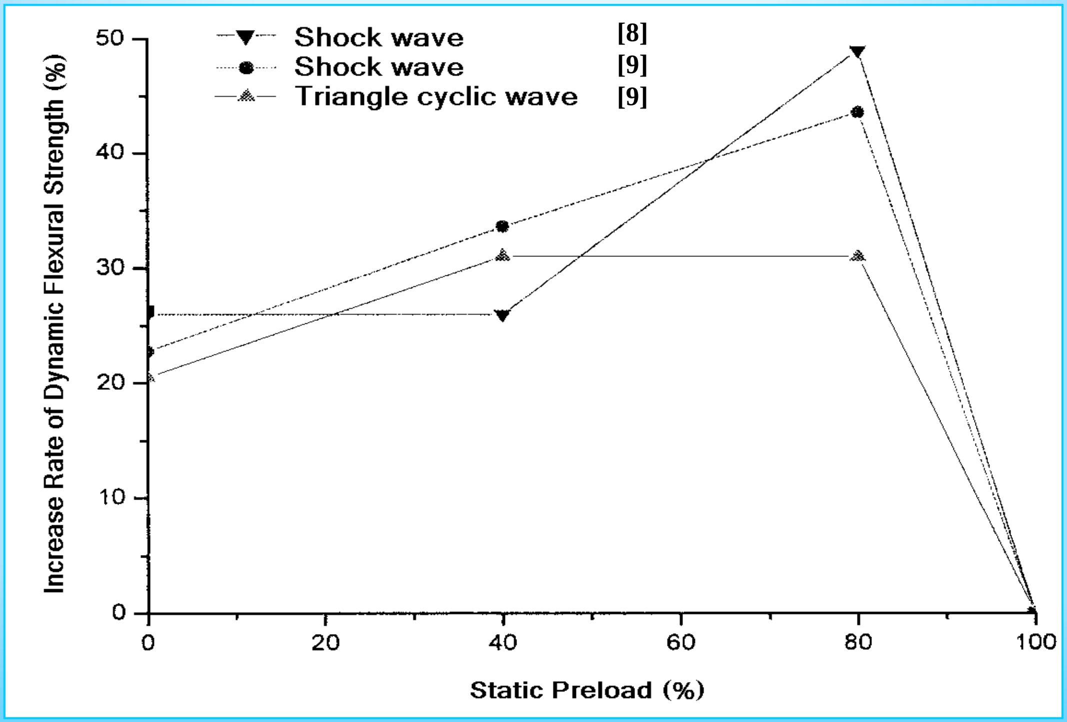
Up to now most of the study of dynamic strength of dam concrete has focused on its strength increase under seismic action by comparing the results between unitary dynamic and static tests using small specimens after wet sieving for aggregates.

• ***Recently, the flexural-tensile properties of dam concrete were studied by testing concrete beams simply supported with tri-point loading both in static state and in dynamic state with shock and triangle cyclic waves under different static preloads for fully graded large specimens of 450*450*1700 mm.***



Sketch of test

Among the results one phenomenon turned out to be even somewhat contrary to conventional expectation, that ***the strain-rate effect increased with the static preloads*** **.**

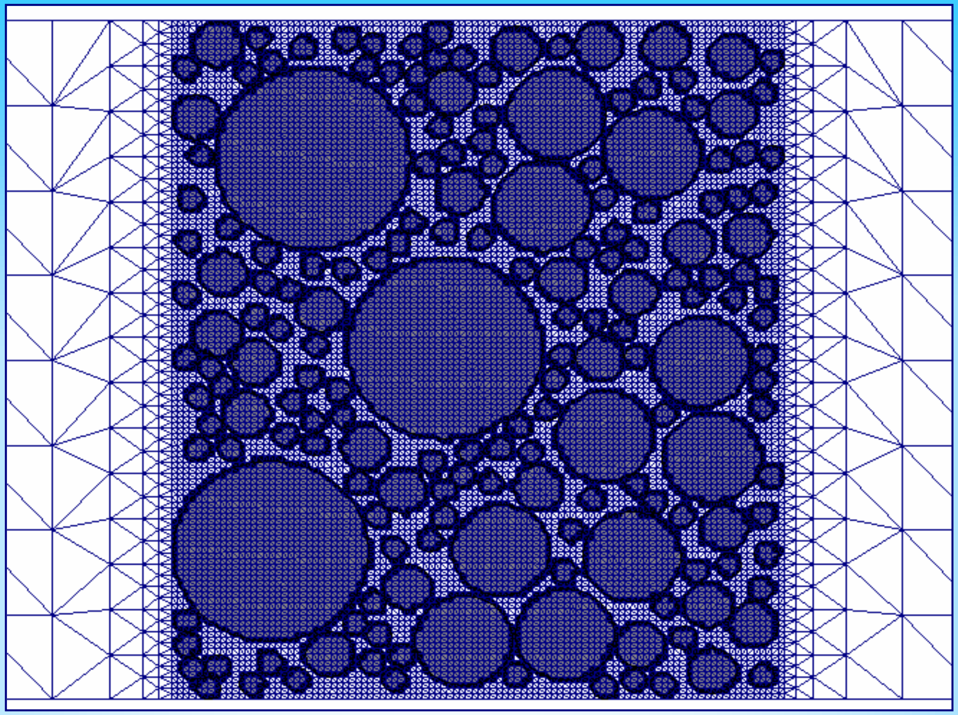


Strain-rate effect of fully graded concrete with different static preloads

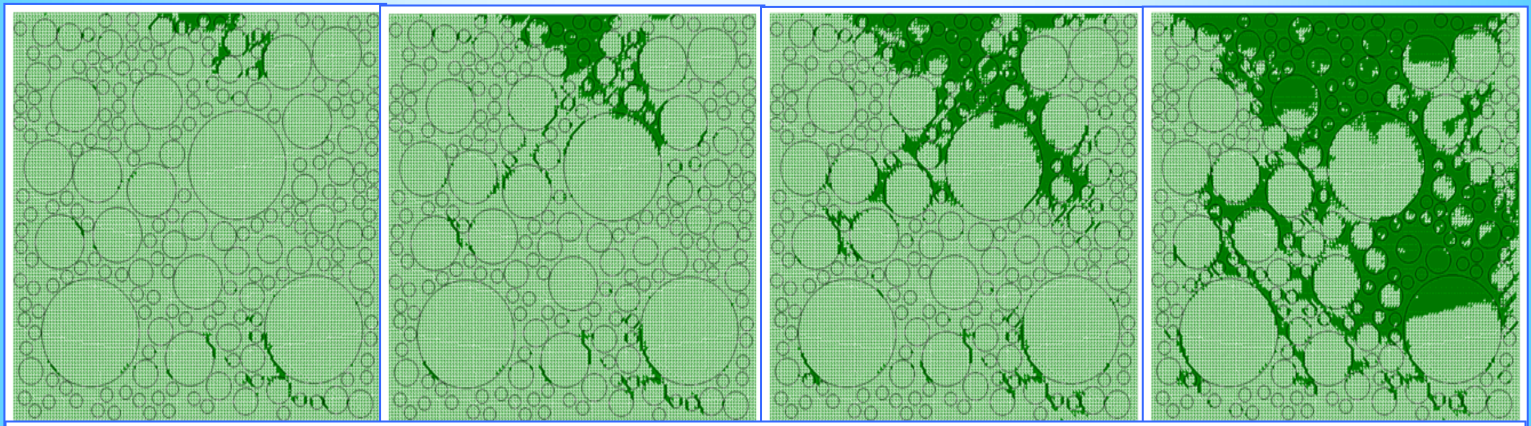
• In order to explain this phenomenon and also to investigate the failure mechanism of dam concrete under dynamic flexural-tensile loading with static preloads, a dynamic numerical analysis of the concrete specimen by method of *meso-mechanical* with consideration of the strain- rate effects and the strain- dependent *dynamic damage constitutive model* has been carried out.

In the meso-mechanical model, the discretization of the full-graded aggregates was completed using finite elements.

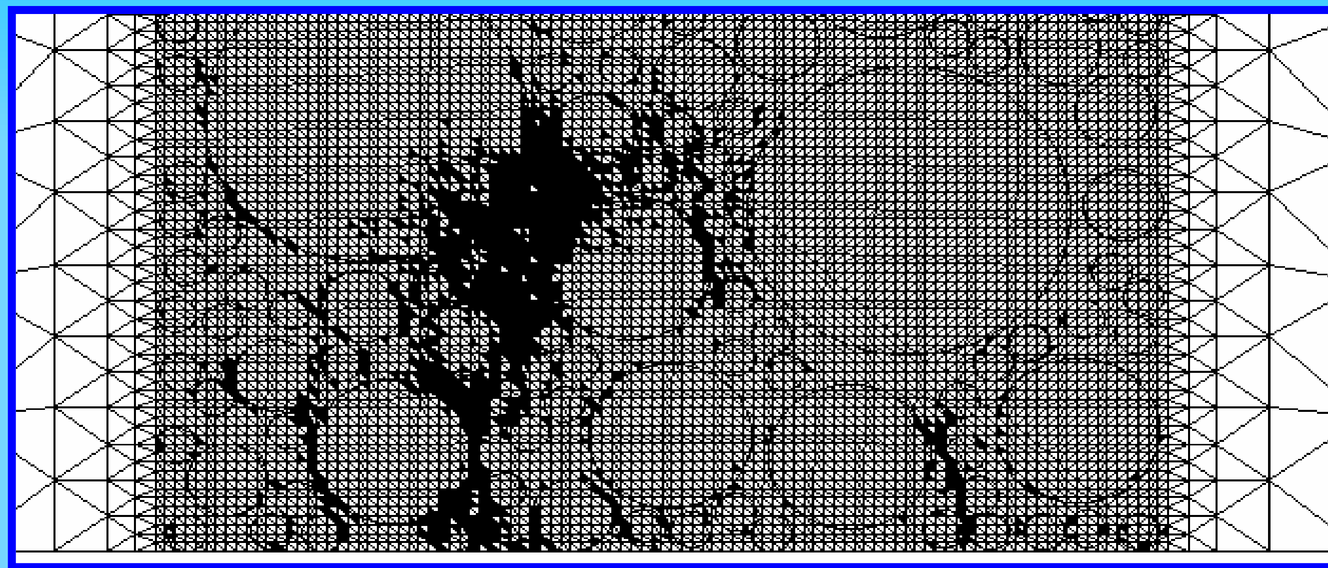
All the locations and the tensile strength of aggregates, cement motor and their interfaces were distributed in a random way.



Finite element mesh of specimen



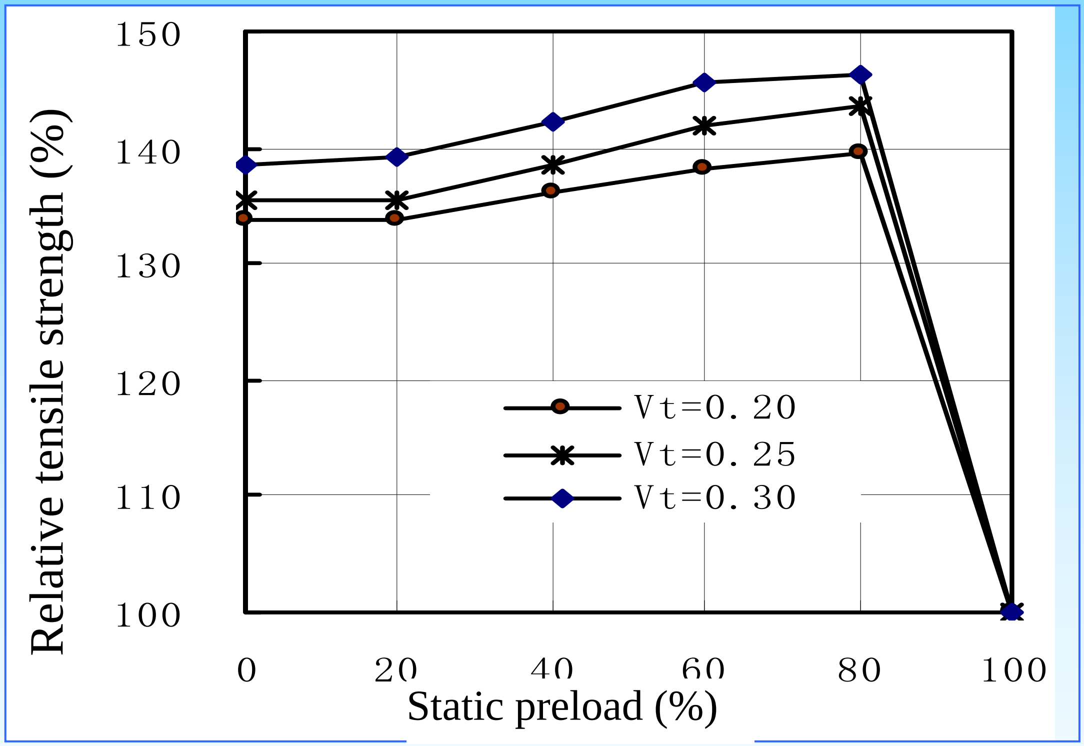
Failure pattern



Failure pattern under static loading

Failure pattern under dynamic loading with static preload

The results of analysis revealed a conception that *increase of dynamic strength related to the strain-rate is intensified by the soften effect of damage caused by the static preload.*



v- variation coefficients of random distributed tensile strength of the interfaces

The experimental phenomenon reasonably explained by the analytical results might be of great significance for seismic safety assessment of large concrete dams.

Conclusions

1. Construction of high dams with huge reservoir in areas of high seismicity is inevitable in order to exploit the abundant hydropower potential and to eradicate poverty in the Western China.

2. Seismic safety of high arch dams is a particular challenge has to be faced and the special attention has to be devoted to for hydropower development in China

3. Some traditional conceptions not suitable for high dams against serious earthquakes must be broken by new ones on the basis of continued and extensive research efforts.

4. There is no insuperable technical barrier to guarantee the seismic safety of high arch dams in hydropower development in China.


THANK YOU