Moscow State University of Railway Engineering

Seismic action abatement method for nuclear power plants and seismic-isolation systems for different structure elements

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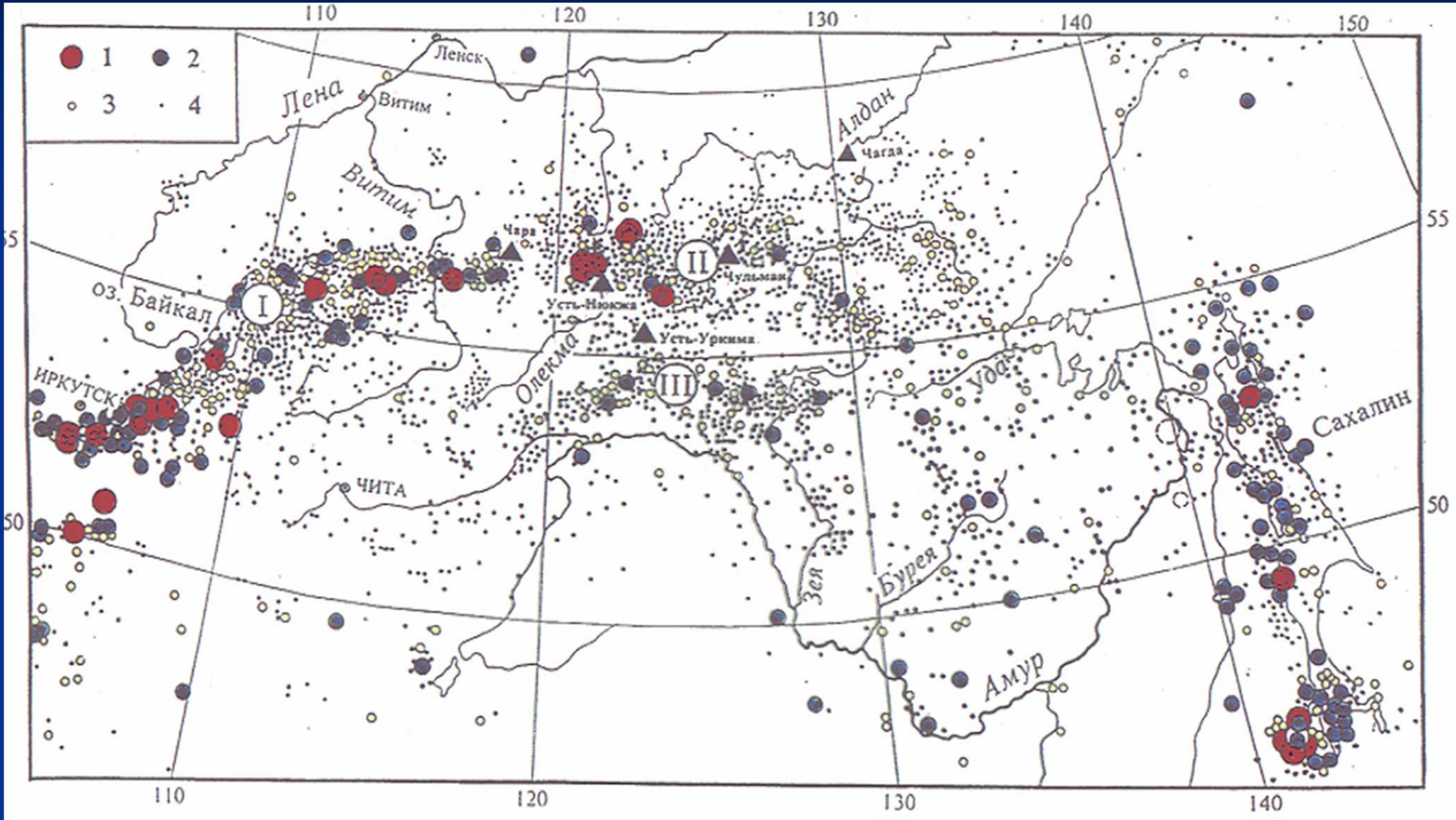
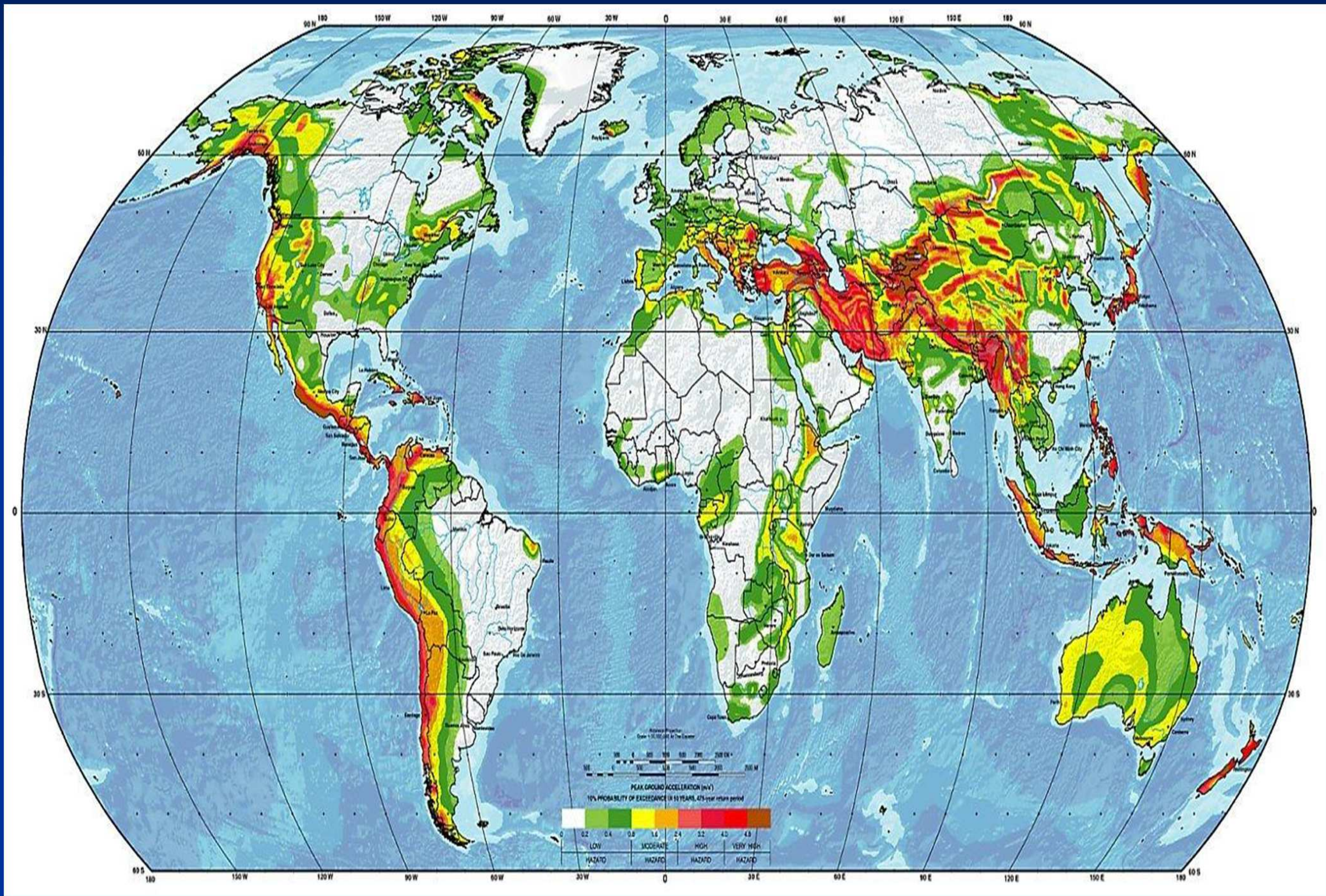
Seismicity of the south-east of Russian Federation



Magnitude: 1-M=5.8-7.6; 2 -M=4,7-5,7; 3 -M=4,0-4,6; 4 -M<4.

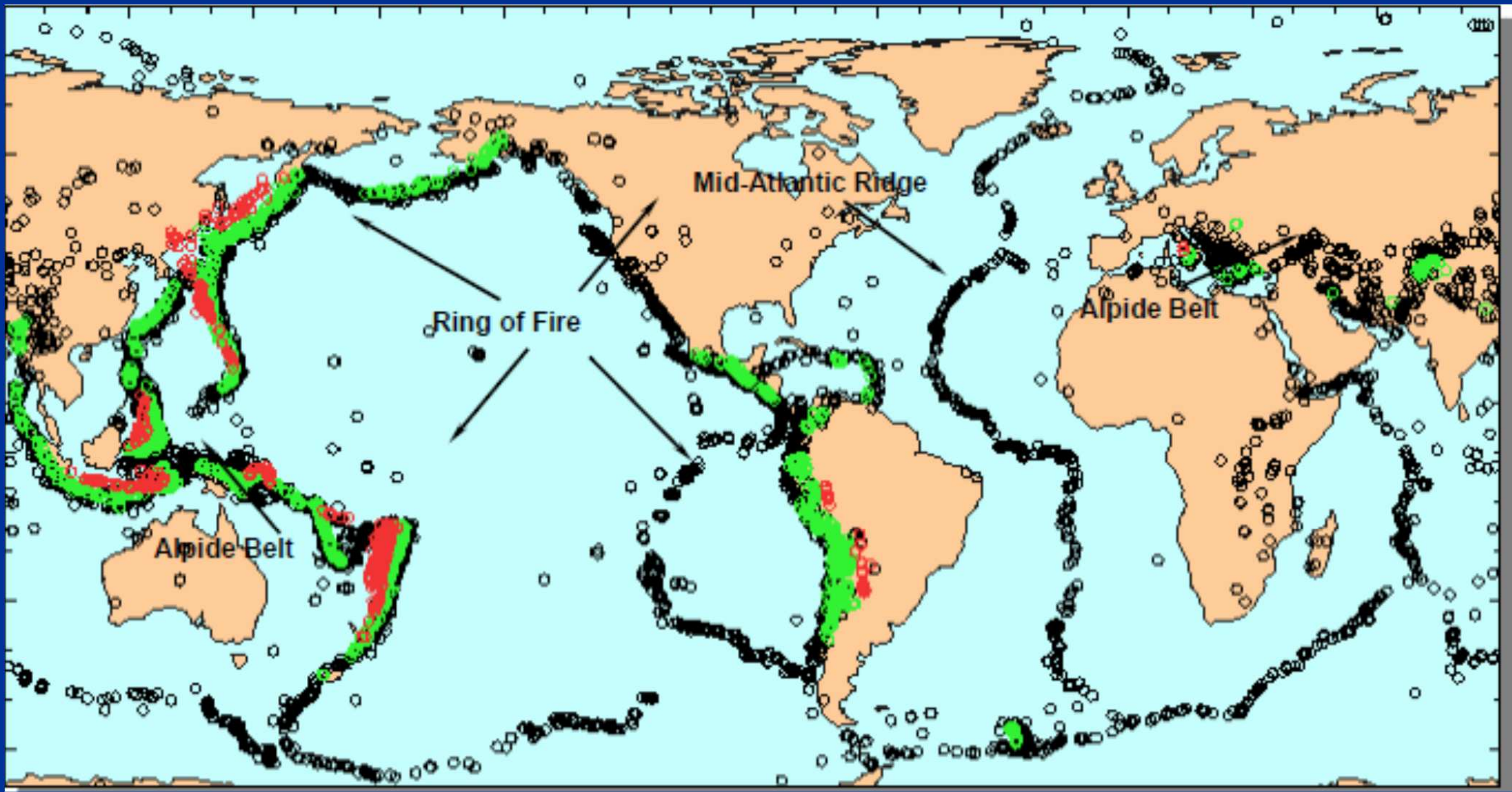
SEISMICITY OF THE WORLD

(D. Giardini, G. Grünthal, K. Shedlock, P. Zhang, 1999)



Seismic belts, where 90% of the world's earthquakes accur

Seismic activity M > 5 since 1980



Introduction

In Russian Federation and all over the world there are a lot of regions with high seismic activity.

It is no secret that in many of these regions energy gap is an essential problem. It should be noted that in many cases for such regions nowadays there is no alternative of nuclear energy.

At present time the new production of power-generating units of nuclear plant is under consideration in Russian Federation.

This year in Russian Federation the New Code "Seismic analysis of Nuclear Structures" has been developed

Seismic analysis of safety-related nuclear structures is a very important and complex problem

There are a lot of different methods and computer programs, recommended for seismic design of the nuclear structures.

We introduce our own method, which may be interesting for researchers, designers and students.

We suppose that our method has preference in comparison with well-known methods on dynamic problem application

Definitions

The functions describing stresses and strain of finite continuum or bodies that are equal to zero outside the domain occupied of this continuum or the body are the finite functions.

An entire function, (integral function), is a complex-valued function that is holomorphic over the whole complex plane.

Every entire function can be represented as a power convergent series.

Any entire function can be represented by a product involving its zeroes. (The Weierstrass factorization theorem).

Paley–Wiener- Schwartz's Theorem

“The Fourier transform of a distribution of compact support on R^n is an entire function on C^n”

The classical Paley–Wiener theorems make use of the holomorphic Fourier transform on classes of square-integrable functions supported on the real line.

The theorem for distribution) was proven later by Laurent Schwartz (1952).

The Main Principles of the Method

The functions which described displacement, stresses and strain of finite continuum or bodies are represented by finite functions that are equal to zero outside the domain occupied of this continuum or the body.

In the right parts of represented in that way differential equations there will be functions describing load, delta functions and its derivatives, concentrated on the boundaries of the domain.

The Right Parts of the Differential equations

The functions of the right describe interaction between the finite continuum and surroundings and represent stresses, strain and displacement on the boundary.

Some of these functions are given. The remainder unknown functions it is necessary to define.

Paley–Wiener- Schwartz's Theorem gives an opportunity to install relations between loads and value of boundary functions and to determine unknown ones.

Boundary Problem Represented in Distribution

Let Ω - is compact domain with S boundary,

$$\Theta(\Omega)=\begin{cases}1, x\in\Omega\\ 0, x\notin\Omega\end{cases}$$ - characteristic function of this domain,

then $U(x)=\{U(x)\}\theta(\Omega)$ – a finite function.

Suppose L - differentiation operator with constant coefficients in Ω domain.

Applying differentiation operator L to the finite function $U(x)$, the differential equation can be written in distribution:

$$LU(x)=q(x)+\sum\mu_k\delta^k(S)+\sum\gamma_k\delta^k(S)$$

$$LU(x) = q(x) + \sum \mu_k \delta^k(S) + \sum \gamma_k \delta^k(S)$$

where $q(x)$ **– load, applied inside domain (finite function),**

μ_k **- given boundary values function** $U(x)$ **and values of its derivatives at the normal intersection of the boundary** S **,**

γ_k **- unknown boundary values function** $U(x)$ **and values of its derivatives at the normal intersection of the boundary** S **,**

$\delta^k(S)$ **- delta functions and its derivatives, concentrated on the boundaries** S **of the domain** Ω**.**

Theorem

“”Unknown boundary values function $U(x)$ and values of its derivatives, can be determined by the values of Fourier transform of the right part the differential equation on zeroes polynomial corresponded to operator L”.

The differential equation becomes, after application of the Fourier transform:

$$L(\upsilon)\tilde{U}(\upsilon) = \tilde{q}(\upsilon) + F\left(\sum \mu_k \delta^k(S)\right) + F\left(\sum \gamma_k \delta^k(S)\right) \qquad (2)$$

where

$\upsilon(\upsilon_1, \upsilon_2, \upsilon_3)$ **- transformation parameters,**

$L(\upsilon)$ **-polynomial corresponded to operator** L**,**

$\tilde{U}(\upsilon)$ **- Fourier transform of finite function** $U(x)$**,**

$\tilde{q}(\upsilon)$ **- Fourier transform of finite function** $q(x)$**,**

$F\left(\sum \mu_k \delta^k(S)\right)$ **and** $F\left(\sum \gamma_k \delta^k(S)\right)$ **- Fourier transform of the boundary finite functions.**

Proof

The equation (2) makes it possible to write the expression for Fourier transform of $U(x)$ function:

$$\tilde{U}(\upsilon)=\frac{\tilde{q}(\upsilon)+F\left(\sum\mu_k\delta^k(S)\right)+F\left(\sum\gamma_k\delta^k(S)\right)}{L(\upsilon)} \qquad (3)$$

It should be noted, that the numerator of this expression is an entire function because it is a sum of entire functions.

The denominator is a polynomial and therefore it can be represented by a product involving its zeroes (the Weierstrass factorization theorem).

According to the Paley–Wiener- Schwartz's theorem $\tilde{U}(\upsilon)$ should be an entire function since it is Fourier transform of finite function.

Proof (continue)

Substitution of polynomial zeros into the functions of the numerator leads to the following system of equation for determination of unknown boundary functions.

$$\tilde{q}(\upsilon)+F\left(\sum\mu_k\delta^k(S)\right)+F\left(\sum\gamma_k\delta^k(S)\right)=0, \quad \forall\,\nu\in C^n:\ L(\upsilon)=0 \qquad \textbf{(4)}$$

These equations complete the proof.

This theorem gives an opportunity to develop an effective method of numerical analysis of seismic wave’s propagation in continuum, its interaction with structures and seismic isolation devises.

Finite element construction

Consider elastic continuum occupied finite domain Ω during time interval $(0,T)$ under load f_j. Let the displacements and stresses are described in a Cartesian coordinate system (x_1, x_2, x_3) in the form of finite function:

$$U_i(x,t) = \{U_i(x_1, x_2, x_3)\}\Theta(\Omega)\Theta(T);$$

$$\sigma_{i,j} = \{\sigma_{i,j}\}\Theta(\Omega)\Theta(T);$$

where $\Theta(\Omega)$ and $\Theta(T)$ are characteristic functions of domain Ω and time interval $(0,T)$.

Differential equations of theory of elasticity for finite continuum in distribution

$$
\begin{aligned}
&\mu U_{j,ii} + (\lambda+\mu) U_{i,jj} - \rho \ddot{U}_j = -F_j + \\
&+[\sigma_{i,j}]_s \cos(\bar{n}x_i)\delta_s + \lambda[[U_j]_s \cos(\bar{n}x_i)\delta_s]_{,j} + \\
&+\mu[[U_i]_s \cos(\bar{n}x_j)\delta_s]_{,i} + \mu[[U_j]_s \cos(\bar{n}x_i)\delta_s]_{,i} - \\
&-\rho[U_j]_{t=0}\dot{\delta}(t) + \rho[U_j]_{t=T}\dot{\delta}(t-T) - \\
&-\rho[\dot{U}_j]_{t=0}\delta(t) + \rho[\dot{U}_j]_{t=T}\delta(t-T).
\end{aligned}
\tag{5}
$$

$[U_i]_s$ и $[\sigma_{i,j}]_s$ **- discontinuities of functions** U_i **и** $\sigma_{i,j}$ **at the normal intersection of the boundary** S **from inside of the** Ω **domain. Since the functions** U_i **and** $\sigma_{i,j}$ **outside of this domain equal zeros the values of these discontinuities** $[U_i]_s$ **и** $[\sigma_{i,j}]_s$ **are boundaries values of the functions.**

Fourier Transform of the Equations

$$[\nu_1^2+\nu_2^2+\nu_3^2-\beta^2\omega^2]\tilde{U}_i+(\beta^2-1)\tilde{U}_j\nu_i\nu_j=\frac{\tilde{X}_i}{\mu} \qquad (6)$$

ν_1,ν_2,ν_3 - **transformation parameters, corresponding to space coordinates,**

ω- **transformation parameter, corresponding to** τ **variable (**$\tau=c_P t$**),**

$\beta=\frac{c_P}{c_S}$ - **where** c_P **and** c_S **are the velocities of compressional and shear waves in medium,**

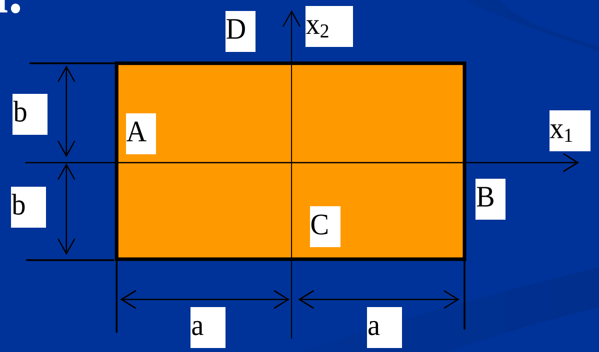
$\tilde{U}_j$- **the Fourier transform of functions** U_j **(displacements),**

$\tilde{X}_i$ **– the Fourier transform of the right parts of equation (5) .**

Discretization Elastic Continuums

For numerical evaluation of dynamic theory elasticity problems were developed different finite elements. The finite element discretization of an elastic continuum (in the general case nonhomogeneous) is performed such as to assure that medium characteristics inside of the element are constant.

The elements may have trapezoidal or rectangle form with sides parallel to coordinate axes (Fig. 1). As an example consider an elements rectangle form.



Representation Fourier Transform of Finite Functions by Taylor Series

For finite element equation remarkable properties of the Fourier transform finite functions may be used:

- Fourier transforms of finite functions may be represented by Taylor series.

The every "n" term of these series is a momentum of the original.

Example, for finite on interval $\left[-a,a\right]$ function $f(x)$ it Fourier transform may be represented in the form:

$$\tilde{F}(\nu)=\int_{-a}^{a} f(x)dx+\frac{\nu}{i}\int_{-a}^{a} xf(x)dx+\frac{\nu^2}{2(i)^2}\int_{-a}^{a} x^2 f(x)dx+\cdots \qquad (7)$$

The equations for the plain rectangular element (Fig.1)

$$
\begin{aligned}
&(-(\lambda+2\mu)\nu_1^2-\mu\nu_2^2+\rho\omega^2)\tilde{U}-(\lambda+\mu)\nu_1\nu_2\tilde{V}=-F_1-\\
&-(\lambda+2\mu)i\nu_1[e^{-i\nu_1 a}\tilde{U}_A-e^{i\nu_1 a}\tilde{U}_B]-\mu i\nu_2[e^{-i\nu_2 b}\tilde{U}_C-e^{i\nu_2 b}\tilde{U}_D]-\\
&-\lambda i\nu_1[e^{-i\nu_2 b}\tilde{V}_C-e^{i\nu_2 b}\tilde{V}_D]-\mu i\nu_2[e^{-i\nu_1 a}\tilde{V}_A-e^{i\nu_1 a}\tilde{V}_B]+\\
&+[e^{-i\nu_1 a}\tilde{\sigma}_A-e^{i\nu_1 a}\tilde{\sigma}_B]+[e^{-i\nu_2 b}\tilde{\tau}_C-e^{i\nu_2 b}\tilde{\tau}_D];
\end{aligned}
$$

(8)

$$
\begin{aligned}
&(-(\lambda+2\mu)\nu_2^2-\mu\nu_1^2+\rho\omega^2)\tilde{V}-(\lambda+\mu)\nu_1\nu_2\tilde{U}=-F_2-\\
&-\lambda i\nu_2[e^{-i\nu_1 a}\tilde{U}_A-e^{i\nu_1 a}\tilde{U}_B]-\mu i\nu_1[e^{-i\nu_2 b}\tilde{U}_C-e^{i\nu_2 b}\tilde{U}_D]-\\
&-\mu i\nu_1[e^{-i\nu_1 a}\tilde{V}_A-e^{i\nu_1 a}\tilde{V}_B]-(\lambda+2\mu)i\nu_2[e^{-i\nu_2 b}\tilde{V}_C-e^{i\nu_2 b}\tilde{V}_D]+\\
&+[e^{-i\nu_2 b}\tilde{\sigma}_C-e^{i\nu_2 b}\tilde{\sigma}_D]+[e^{-i\nu_1 a}\tilde{\tau}_A-e^{i\nu_1 a}\tilde{\tau}_B].
\end{aligned}
$$

Equations for boundary functions definition

For every side of the element it is necessary to find four boundary functions U, V, σ, τ (corresponding horizontal and vertical displacements, normal and tangential stress).

For definition 16 boundary functions it is necessary to have16 conditions.

Eight conditions may be obtained by using boundaries conditions on every side of element or using equality of displacements and stress on the sides of the neighboring elements.

The additional eight equations can be obtained by using the above proved theorem.

Zeros set of the polynomial corresponding to the system (8) for plane case can be written in the form:

$$[\nu_1^2 + \nu_2^2 - (\omega / c_2)^2 = 0 \text{ and } [\nu_1^2 + \nu_2^2 - (\omega / c_1)^2 = 0$$

Condition Equation Derivation

Expanding into Taylor series the left and the right part of the equations (8) equate the left and the right part of the equations when $\nu_1 = 0$ and when $\nu_2 = 0$. The above-mentioned theorem lets formulate the following conditions:

- the right part of the first equations of the system (8) must be equal zero at $(0, \pm\omega/c_S)$ and $(\pm\omega/c_P, 0)$,
- the right part of the second equations of the system (8) must be equal zero at $(0, \pm\omega/c_P)$ and $(\pm\omega/c_S, 0)$.

It deserves to be mentioned that at $\nu_1 = 0$ and $\nu_2 = 0$ the equation system (8) uncouples into two independent equations and polynomials zeros set degenerates into acnodes: $\pm\omega/c_P$ and $\pm\omega/c_S$.

For the elements small in comparison with the wave-length equations can be simplified and after some elaboration may be represented in the form:

$$1)\ [U_C + U_D] - [U_A + U_B] = 0;$$

$$2)\ [\tau_C + \tau_D]/2 + \mu([U_C - U_D]/2b + [V_A - V_B]/2a) = 0;$$

$$3)\ 4ab\rho\omega^2[U_A + U_B]/2 - 2b[\sigma_A - \sigma_B] - 2a[\tau_C - \tau_D] = 0;$$

$$4)\ [\sigma_A + \sigma_B]/2 + (\lambda + 2\mu)[U_A - U_B]/2a + \lambda[V_C - V_D]/2b = 0;$$

$$5)\ 4ab\rho\omega^2[V_C + V_D]/2 - 2a[\sigma_C - \sigma_D] - 2b[\tau_A - \tau_B] = 0;$$

$$6)\ [\sigma_C + \sigma_D]/2 + \lambda[U_A - U_B]/2a + (\lambda + 2\mu)[V_C - V_D]/2b = 0;$$

$$7)\ [V_A + V_B] - [V_C + V_D] = 0;$$

$$8)\ [\tau_A + \tau_B] - [\tau_C + \tau_D] = 0; \qquad (10)$$

Physical sense of these equations

The 1-th and the 7-th equations correspond to the continuity law.

The 2-th, 4-th and the 6-th equations correspond to Hook’s law.

The 3-th and the 5-th equations correspond to the centers of masses moving law.

The 8-th equation corresponds to the twoness law.

Advantages of the Method

1. There is no need to use nonlogical modeling continuum by lamped masses.

2. The unknown parameters of the algebraic systems are directly the stresses and displacements of the elements surfaces.

3. It is possible to construct semi-infinite elements for describing transmitting boundaries.

4. It is possible to use three-dimensional elements for analyzing three-dimensional effects.

5. The method may be used for soil structure interaction analysis in the time or frequency domain.

6. Nonlinear analysis may be used for design soil structure interaction in time domain.

Disadvantages of the method

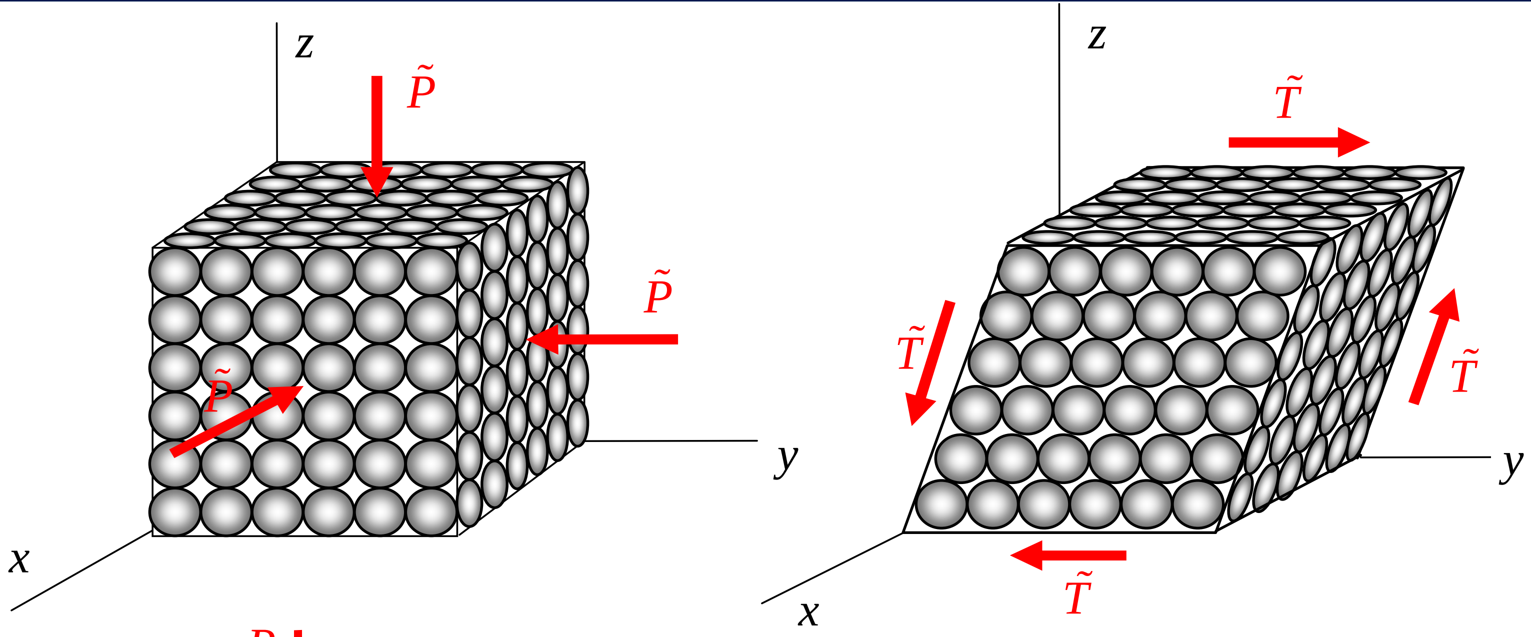
Large number degrees of freedom of elements:

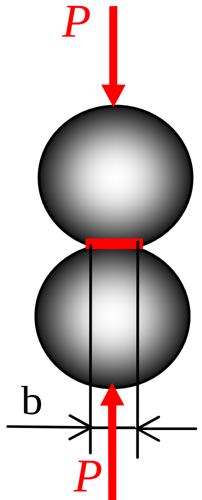
-16 degrees of freedom and 8 equations for the plain elements,

- 36 degrees of freedom and 18 equations for the tree dimensional elements.

But it should be noted, that these disadvantages for modern computer engineering present no difficulty.

Model of unconsolidated granular medium





Hertz relations

$$b = \left[\frac{3(1-\nu_s^2)rP}{4E_s}\right]^{1/3}$$ -radius of flat circle contact,

$$s = \left[\frac{9(1-\nu_s^2)^2 P^2}{2E_s^2 r}\right]^{1/3}$$ - approachment of the two tangent spheres centers

Longitudinal and Transverse Waves Speeds in Unconsolidated Granular Medium

$$c_P = \left[\frac{3E_s^2\tilde{P}}{8(1-\nu_s^2)^2}\right]^{1/6}\left(\frac{6}{\pi\rho_s}\right)^{1/2} \qquad c_P = A_P\sqrt[6]{\tilde{P}}$$

$$c_S = \frac{\left[81(1-\nu_s^2)E_s^2\tilde{P}\right]^{1/6}}{\left[(2-\nu_s)(1+\nu_s)\pi\rho_s\right]^{1/2}} \qquad c_S = A_S\sqrt[6]{\tilde{P}}$$

E_s, ρ_s and ν_s are constant of the solid of which the spheres are made.

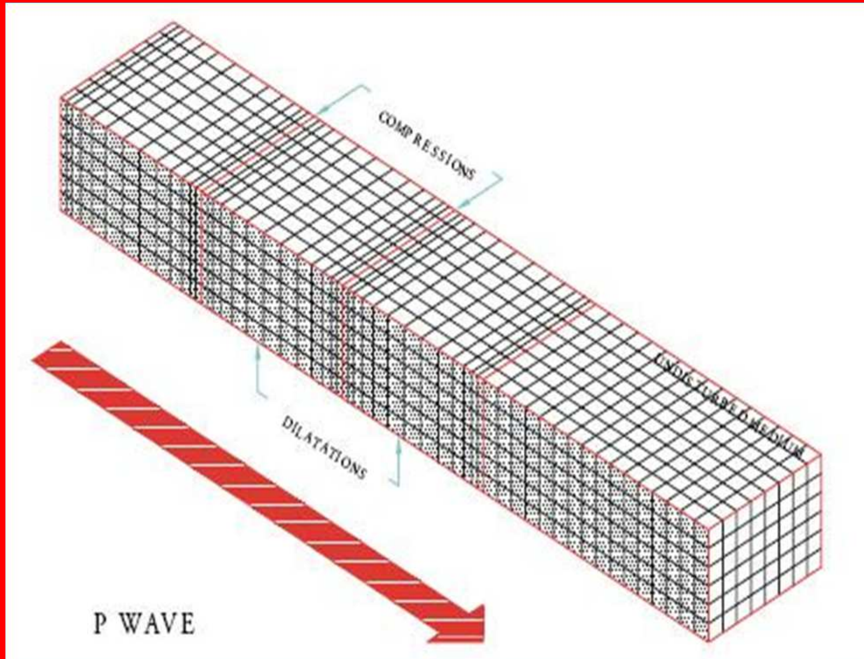
Longitudinal and Transverse Waves Speeds in usual soils (for comparison)

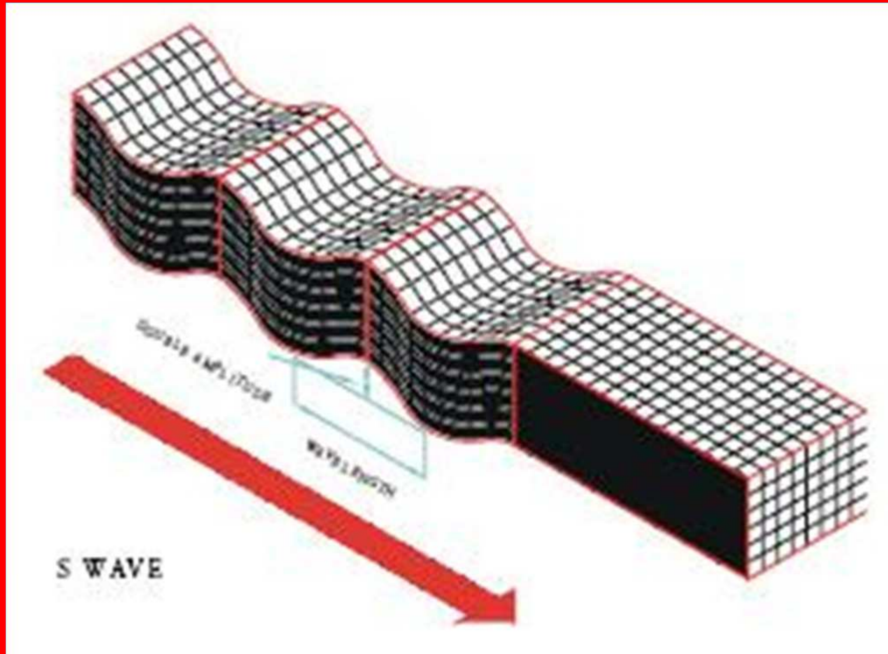
P waves speed

$$\alpha = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

S waves speed

$$\beta = \sqrt{\frac{\mu}{\rho}}$$





Artificial and Semi-artificial Material for seismic protection layers

There is a good chance to create an artificial or semi artificial material with necessary properties.

At present time in “Soil Mechanic Laboratory” of the Moscow State University of Railway Engineering the new semi artificial materials are created and tested.

These materials are unconsolidated alloys of polymers and sands with different ratios.

We try to create materials with necessary values of compressional and shear waves speeds as well as necessary values of natural damping.

Site and Seismic Protection Layers Affect on Ground Motion

- soil profile act like filter,

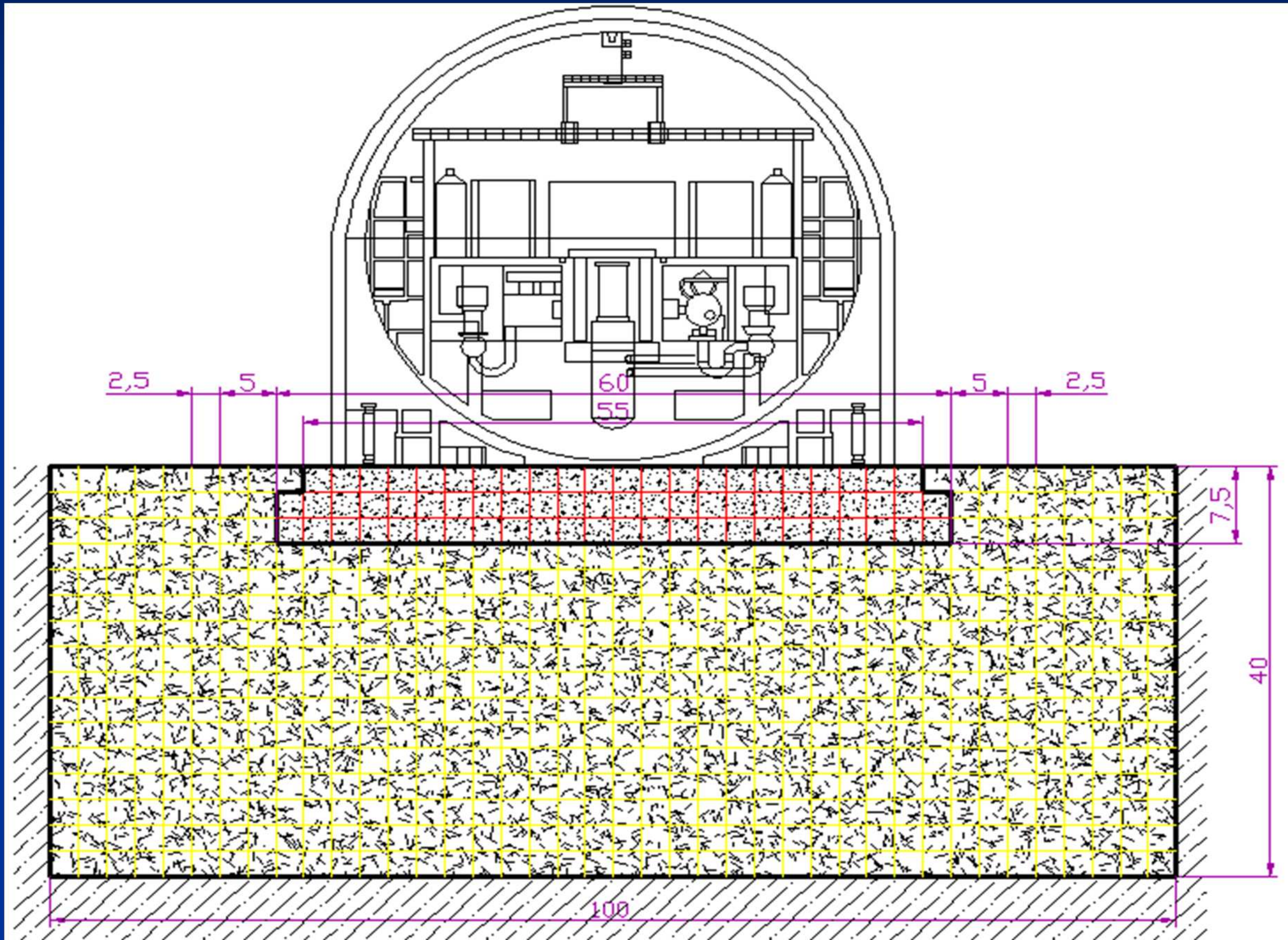
- change in frequency content of motion,

- layering complicates the issue,

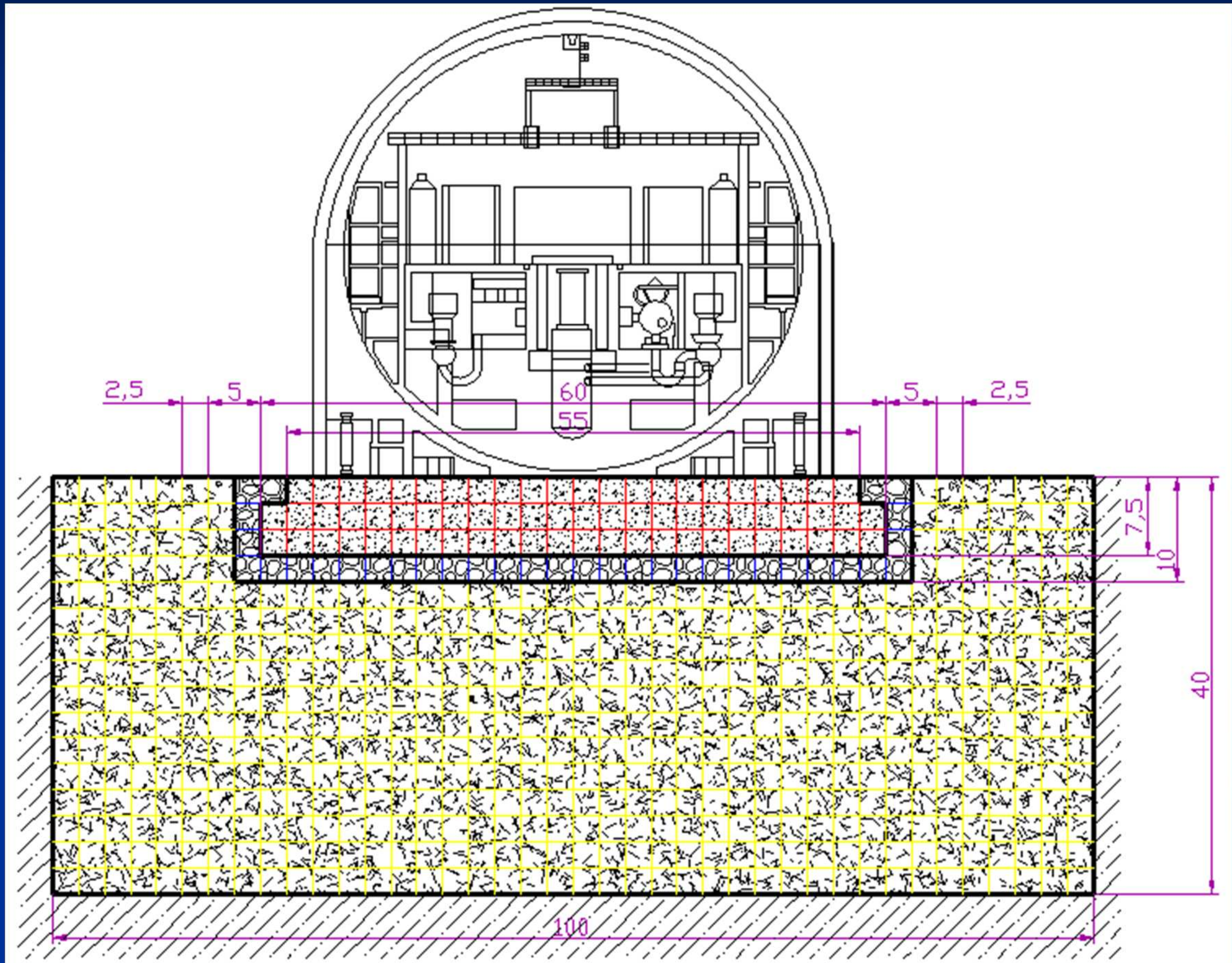
- amplification or de-amplification of ground motions can occur,

- seismic protection layers application requires to perform special calculations.

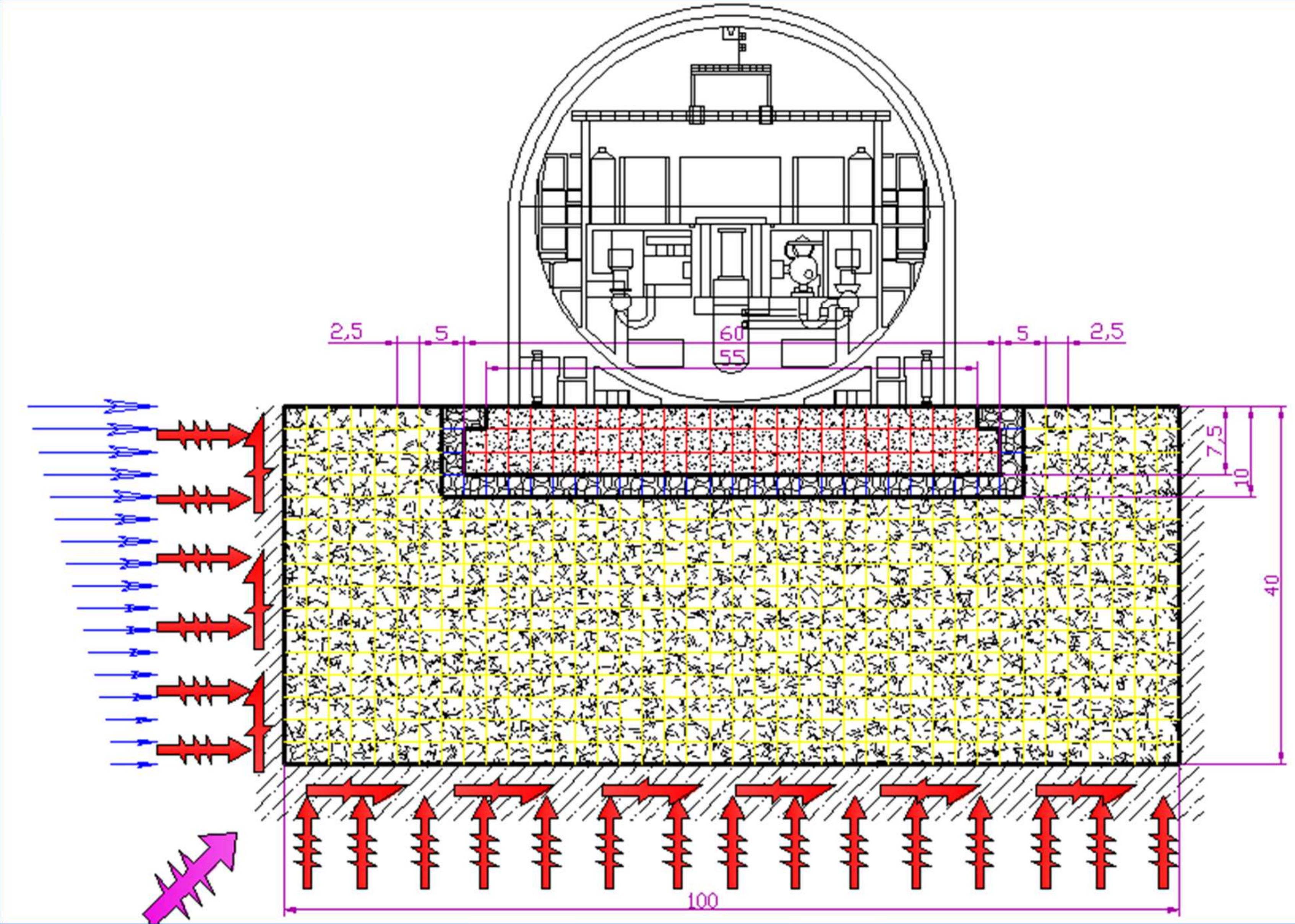
Nuclear power plant without seismic isolation layer under foundation



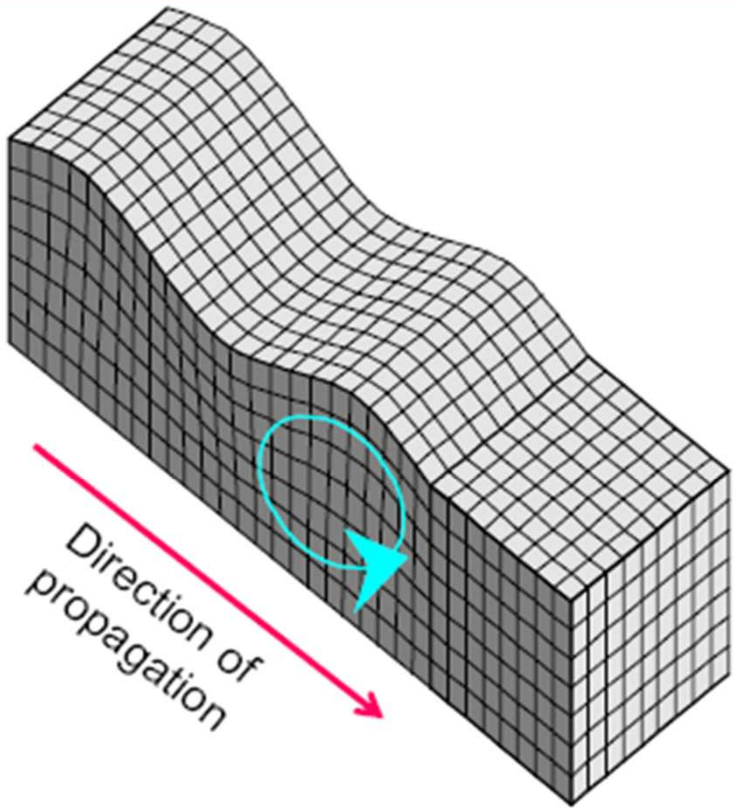
Nuclear power plant with seismic isolation layer under foundation (granular polymer with sand)



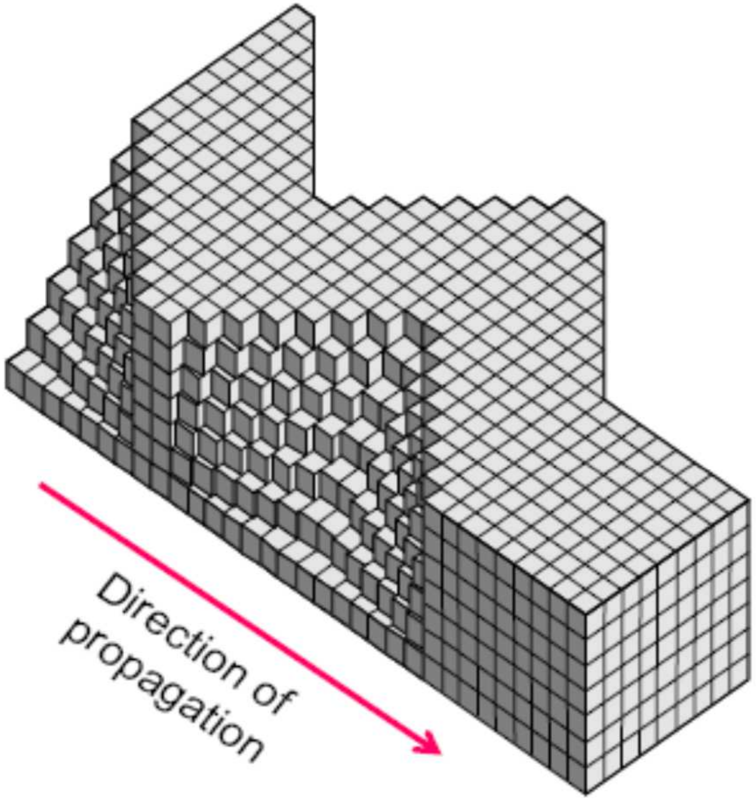
Model of Nuclear power plant with seismic isolation under foundation (layer granular polymer with sand)



Preliminary Analysis indicated that Unconsolidated Granular Layers are the most effective for protective from surface waves

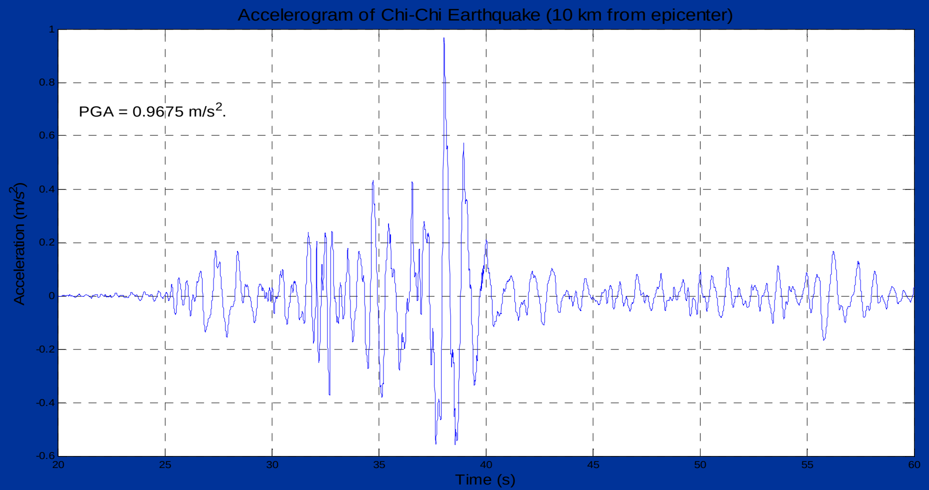


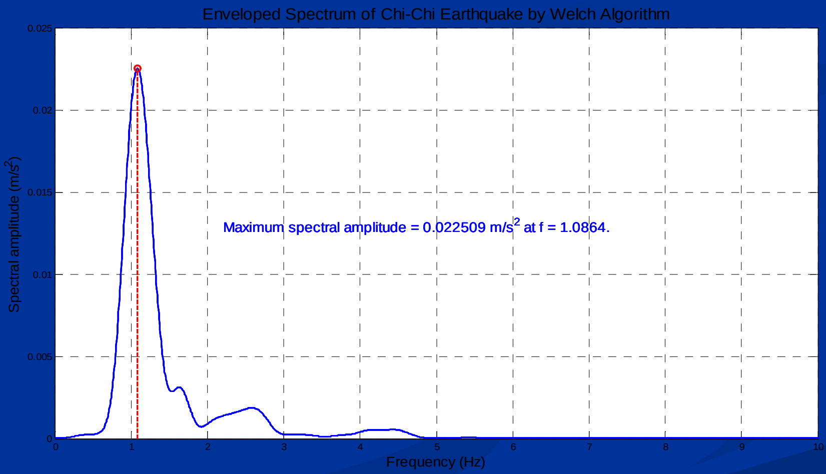
Rayleigh wave



Love wave

Application





Seismic input: ground motions of acceleration time histories, smoothed Fourier spectrum of the Chi Chi earthquake 1999 year

Seismic isolation devices for protection of different elements and units of power plant

In many cases problems of seismic isolation of equipment and different objects of the plant appears

These objects are turbines, reserve control panel etc.

In that case standard seismic isolation devises may be used.

A lot of seismic isolation devises that may be used for protection of nuclear power plant equipment are produced by different companies

Seismic isolation devices

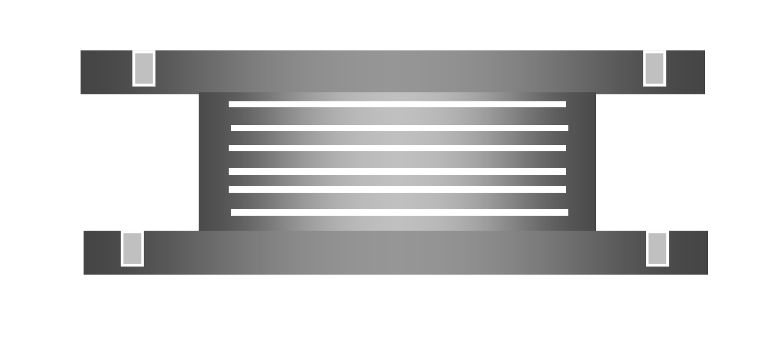
There are very interesting books, where one can find basic requirements, description, modeling and example of different seismic isolation devises:

-“Earthquake engineering” by Nazzal S. Armouti, PH.D,.

-“Earthquake engineering handbook” edited by Wai-Vah Chen and Charles Scawthorn.

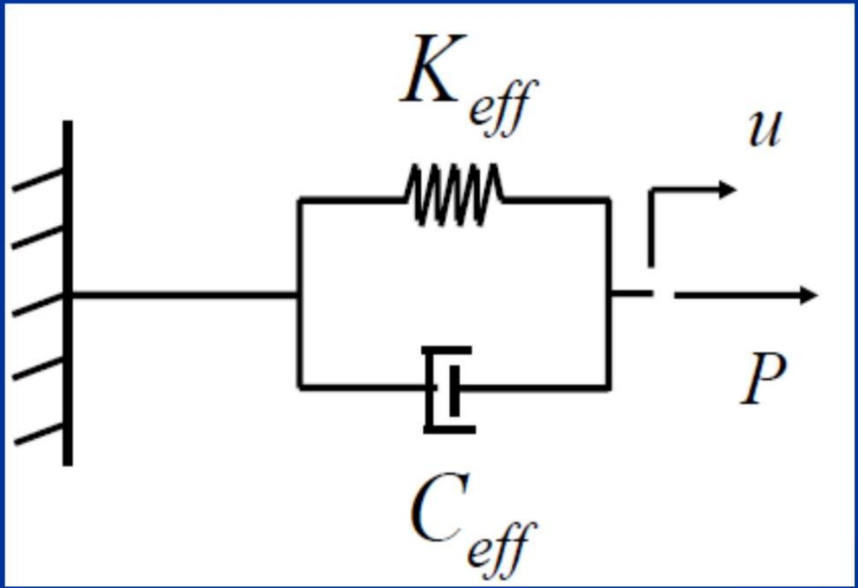
The 17-th chapter “Base Isolation” of the last one has been written by Yeong-bin Yang, Kuo-Chun Chang from Taiwan University, Taipei and Jon-Dar Yau from Tamkang University, Taipei.

Low Damping Natural or Synthetic Rubber Bearing



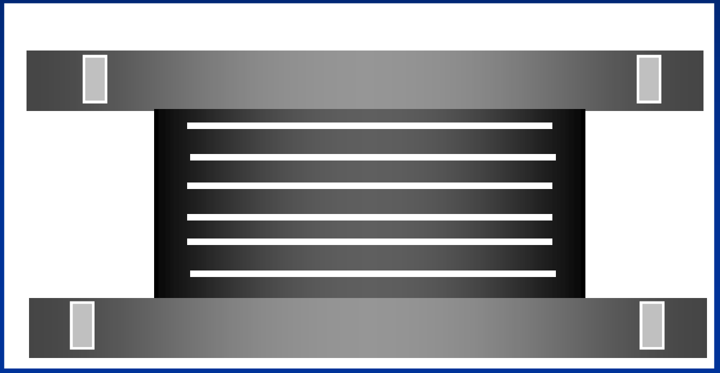
- Linear behavior in shear
- Damping ratio 2-3%
- Simple to manufacture
- Easy to model
- Response not sensitive to Rate of loading, history of loading, temperature, aging

Model

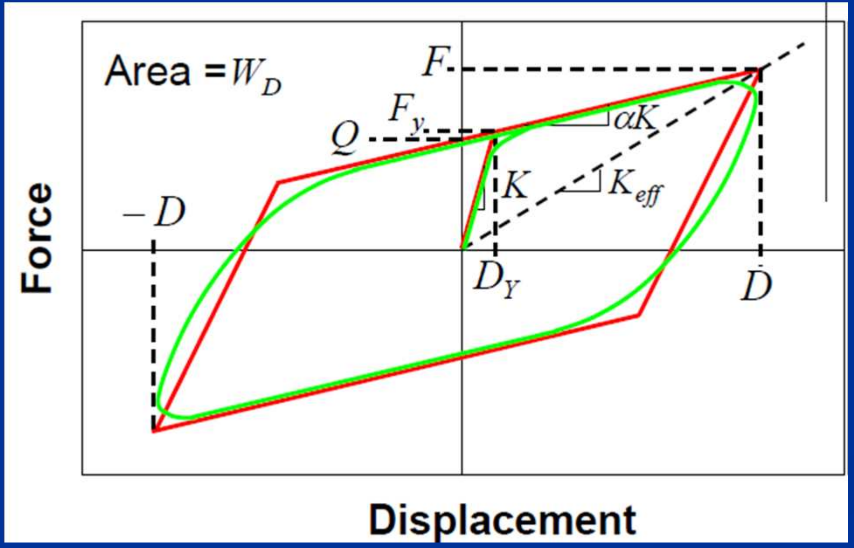


$$P(t) = K_{eff}u(t) + C_{eff}\dot{u}(t)$$

High Damping Natural or Synthetic Rubber Bearing



Idealized hysteretic loop



Linear behavior in shear

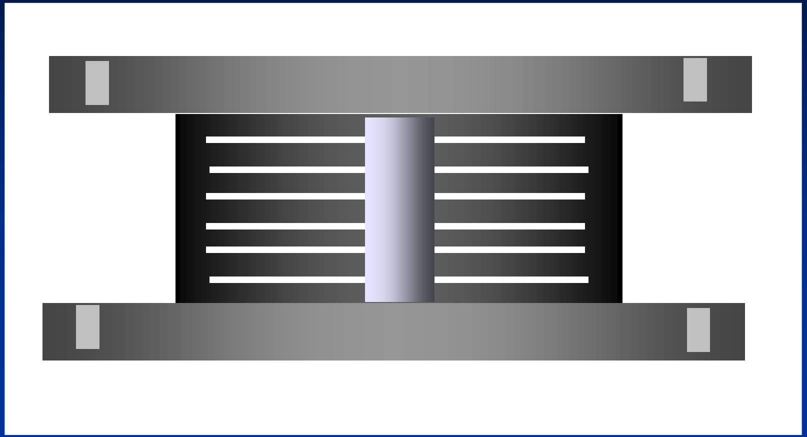
Damping ratio 10-20%

Damping increase by adding extra fine carbon black, oil resin and other fillers

Stiffness and damping depend on:

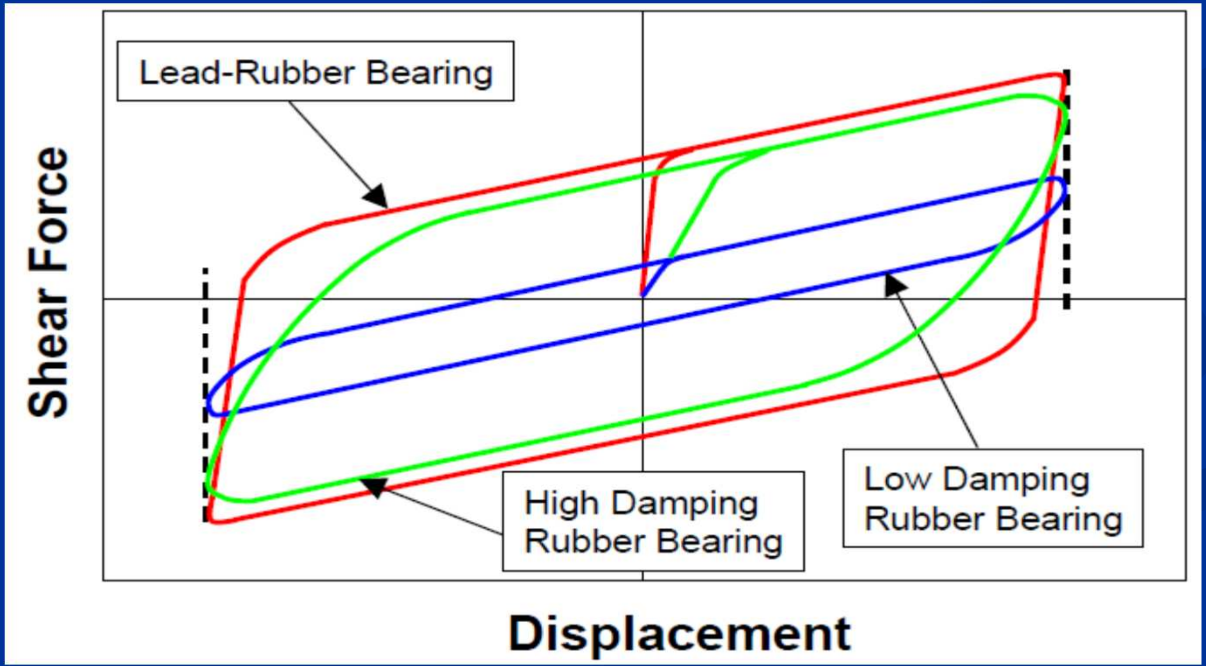
- elastomer and filler,
- contact pressure,
- velocity of loading,
- temperature.

Lead Rubber Bearing



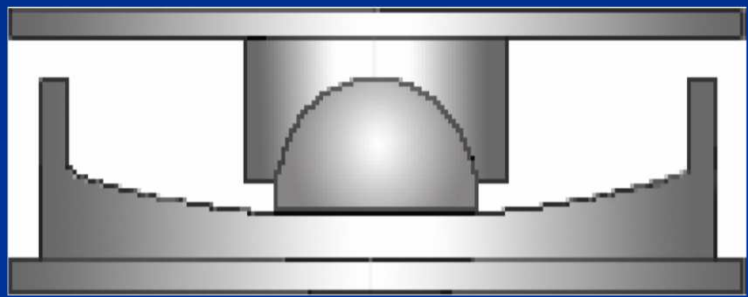
Low damping rubber combined with central lead core
Hysteretic response is strongly displacement-dependent

Hysteretic loops

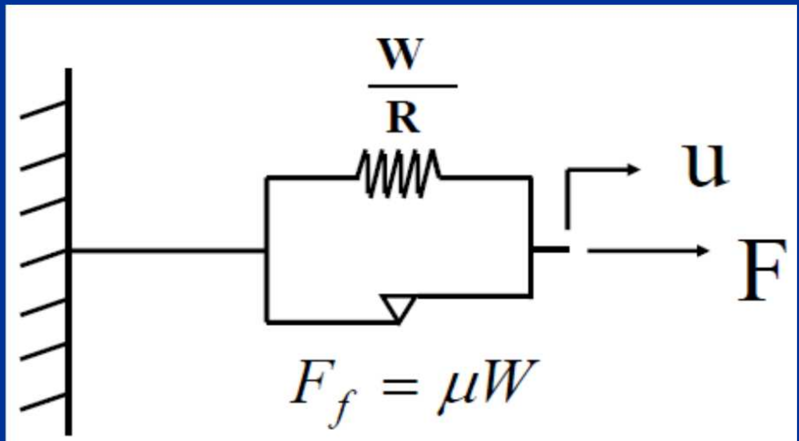


Friction Pendulum Bearings

Model



Mathematical model of friction pendulum bearings



$$F = \frac{W}{R}u + \mu W sign(\dot{u})$$

Passive Energy Dissipation Systems

Velocity dependent systems:

- viscous fluid dampers,
- viscoelastic solid dampers.

Displacement dependent systems:

- metallic yielding dampers,
- metallic friction dampers.

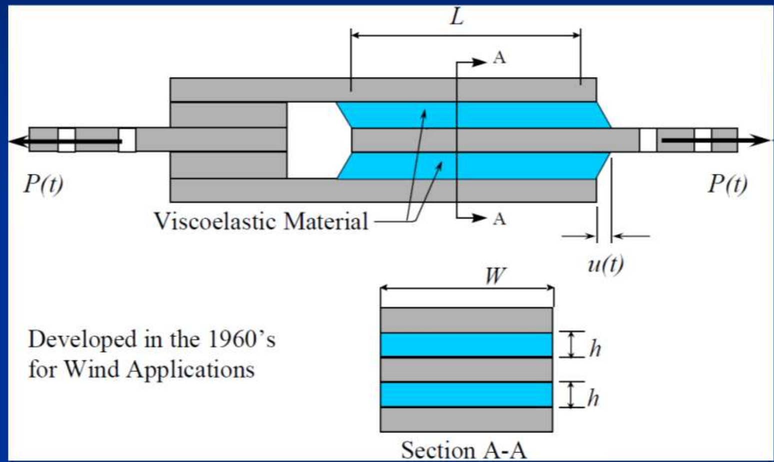
Vibration absorbers:

- tuned mass dampers,
- shape-memory alloys.

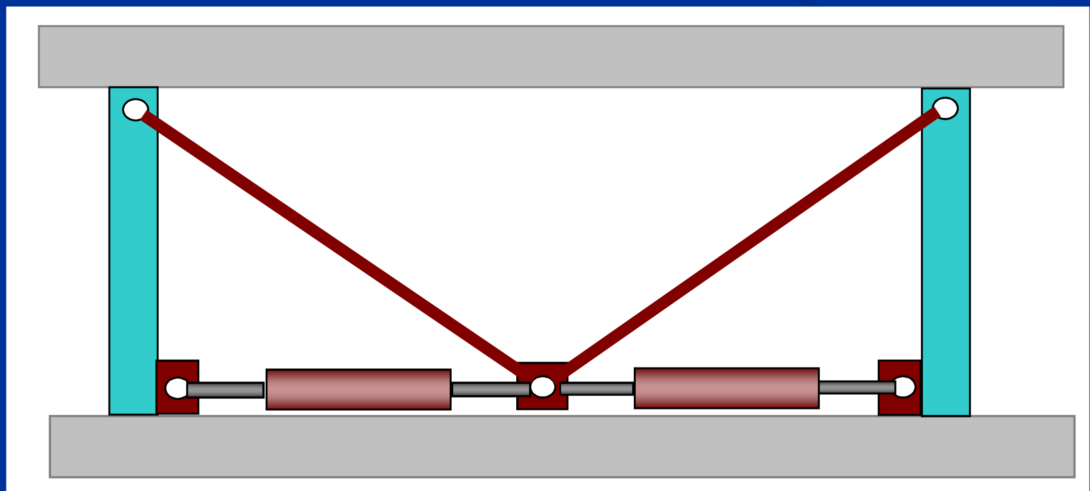
Seismic isolation devices (dampers)

Fluid dampers

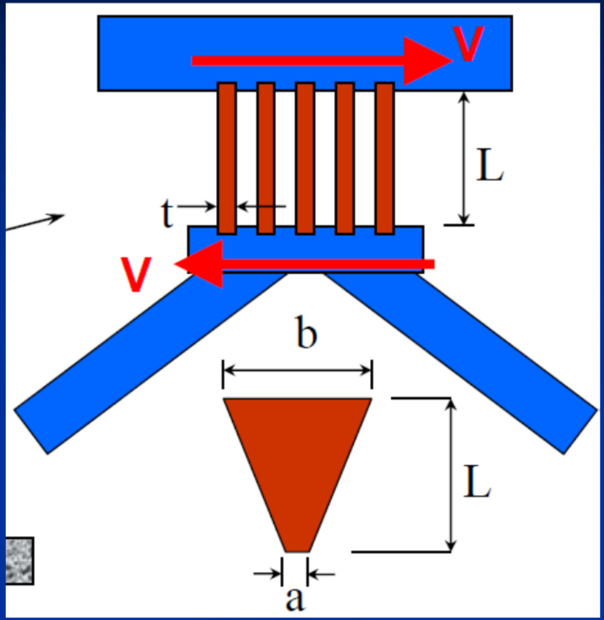
Viscoelastic dampers

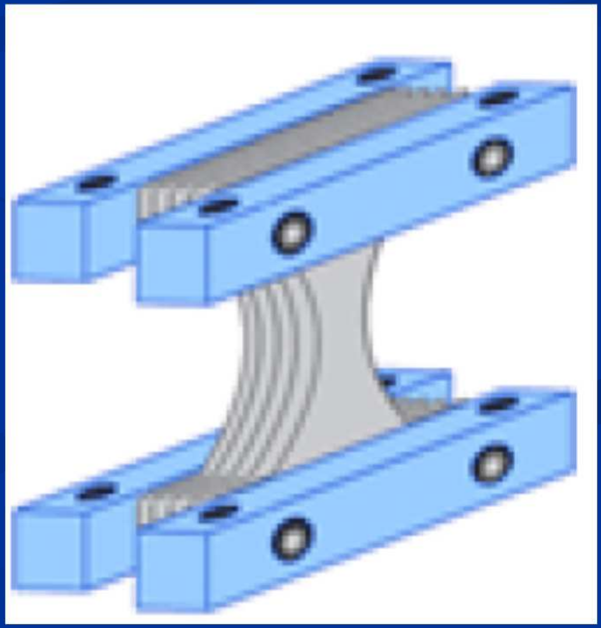


Fluid dampers within chevron brace



Steel Plate Dampers





Conclusion

1. 70% of urban and industrial regions are earthquake prone areas. In many of these regions there are serious deficiencies in the numbers of energy resource.

2. Modern investigations in the field of seismology give an opportunity to present reliable seismic input information for any regions.

3. Nowadays current technology gives an opportunity to produce the new materials with necessary prescribed properties.

Conclusion (continue)

4. At present time in many countries different vibroisolation devices are manufactured.

5. Modern science and engineering gives an opportunity to design and to construct the safety-related nuclear structures in region with high seismic activities

6. In spite of plenty of computer programs for seismic design of structures it is necessary to improve analysis

7. The method based on the properties Fourier transform finite functions gives an computational feasibility seismic analysis of safety-related of nuclear structures.

Thank you!