Tang Prize Foundation
Taipei, September 20, 2018

The Ultimate Earthquake Isolation
A Quantum Jump in Performance

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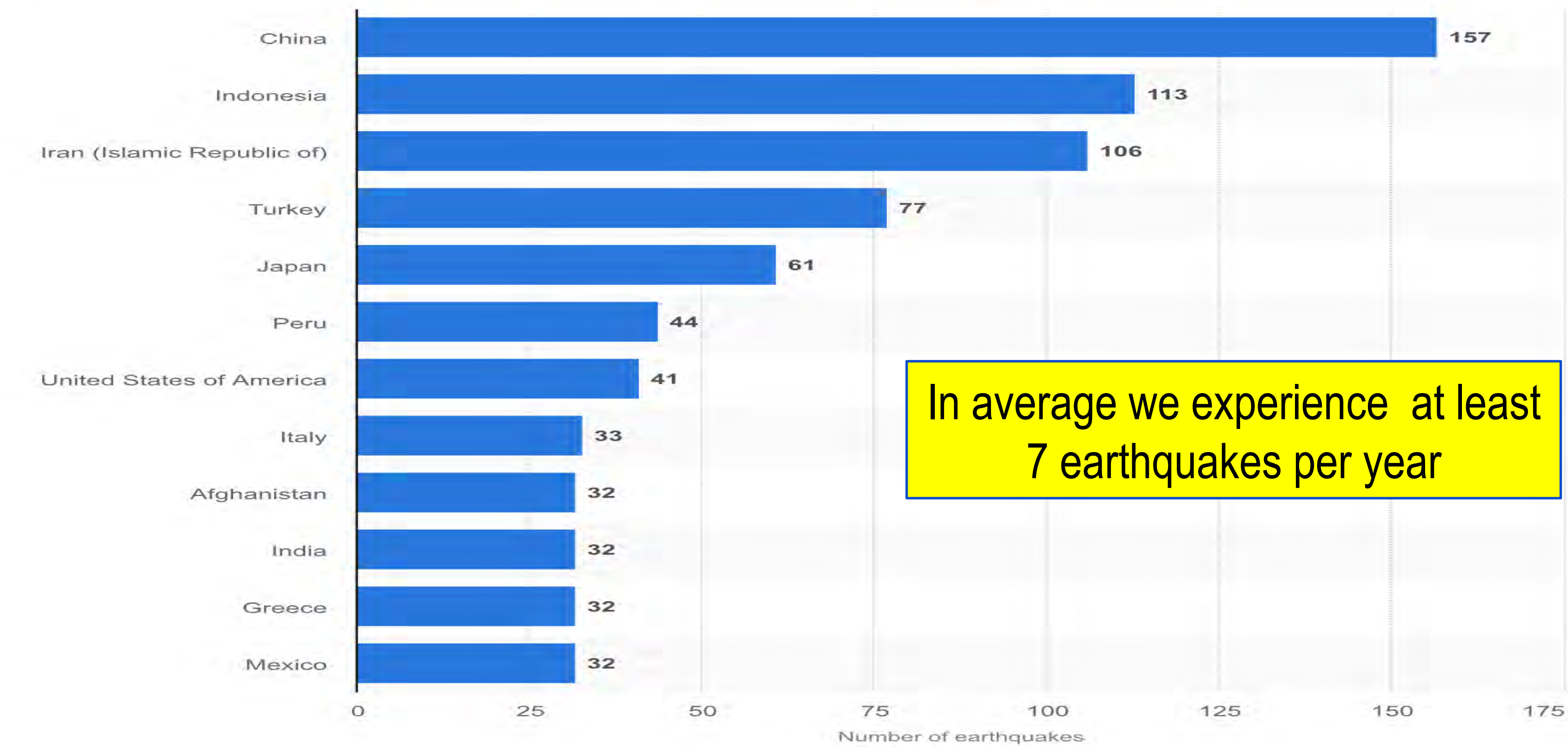
Russia-Taiwan Scientific and Technological Forum 2017

Addressed Problem – 1/2

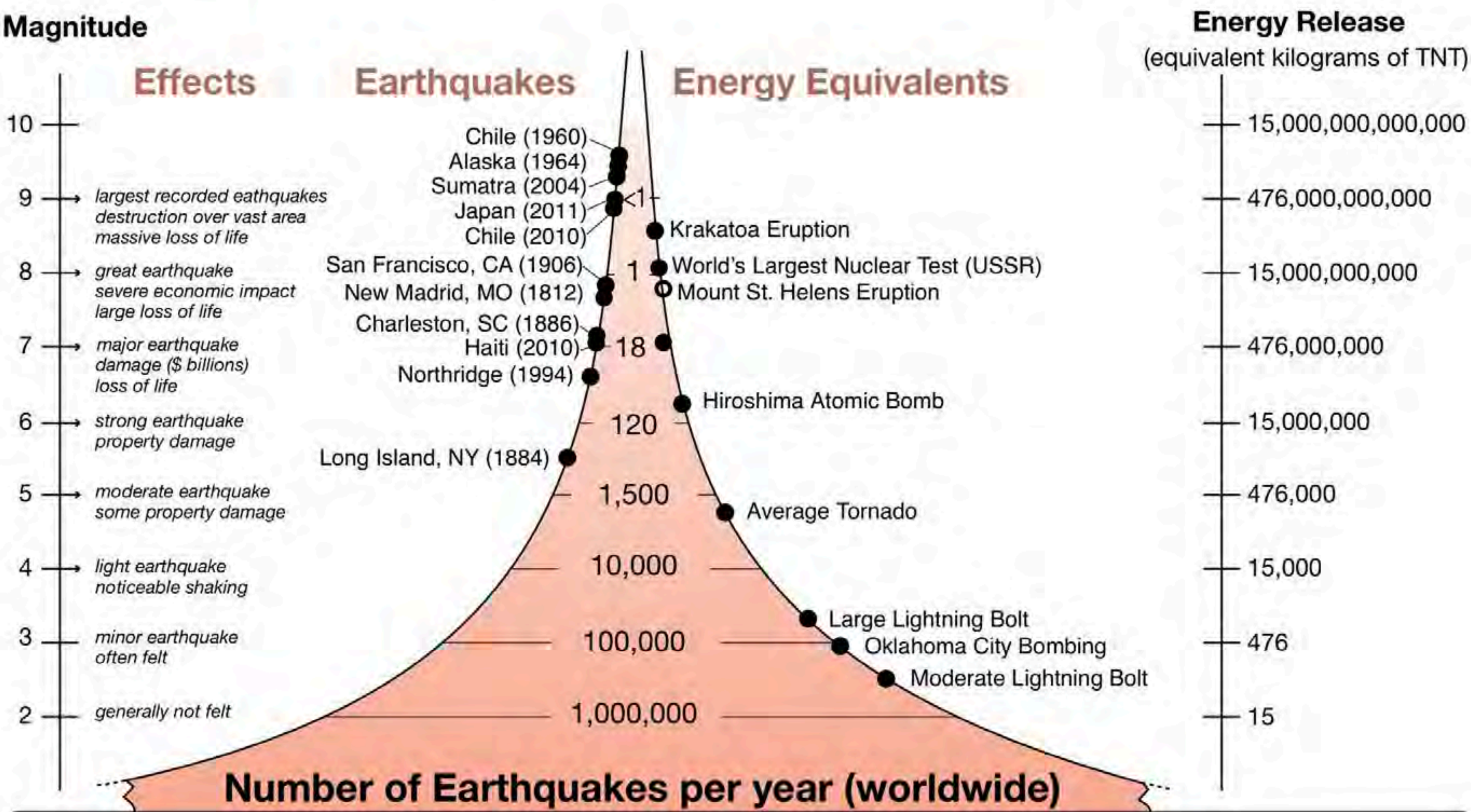
Countries with the most earthquakes 1900-2016

Earthquakes are one of the most devastating problems of the humankind



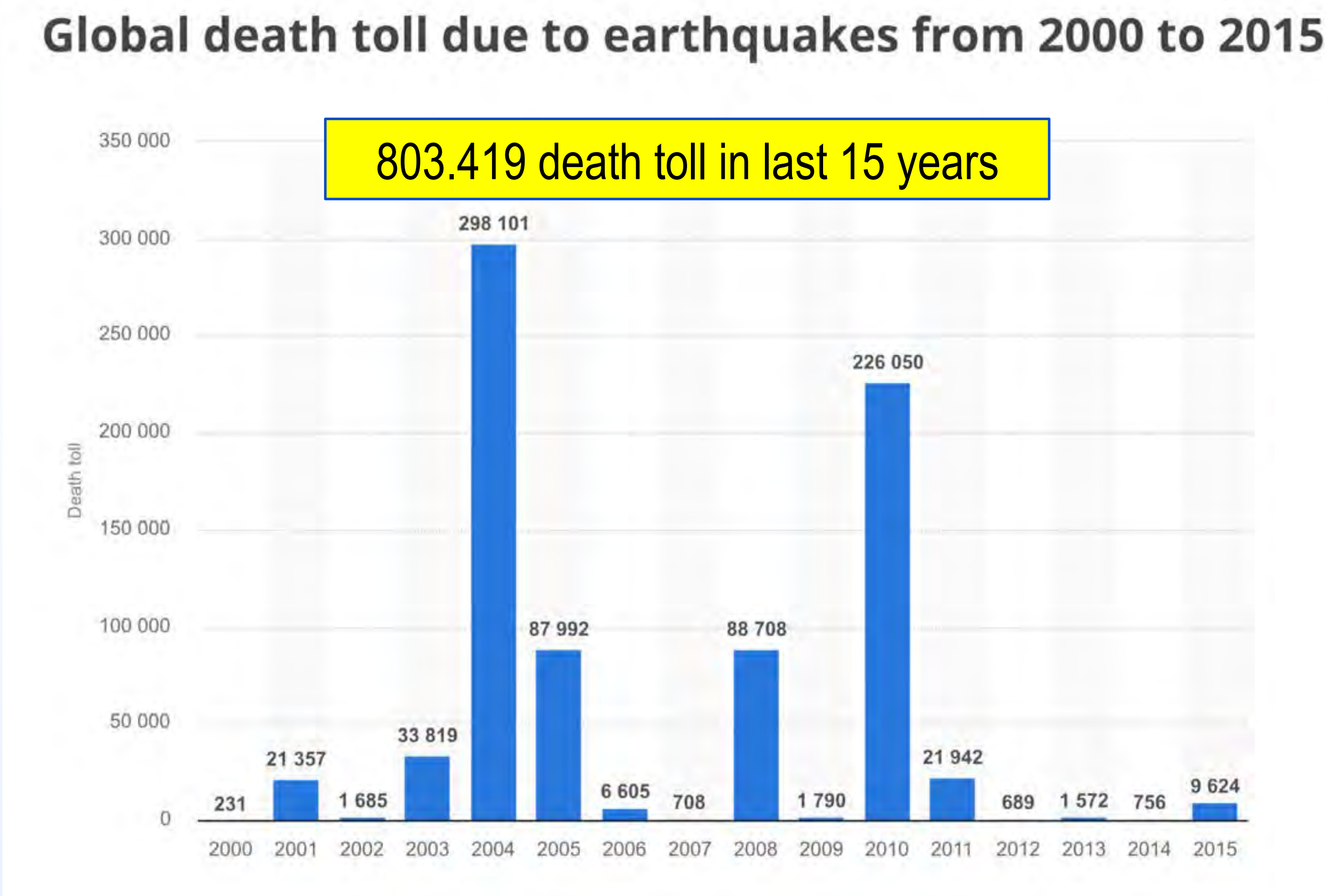
In average we experience at least 7 earthquakes per year

Addressed Problem – 2/2



Many earthquakes were/are orders of magnitude more devastating than the Hiroshima Atomic Bomb

Our Vision: Safer world against earthquakes

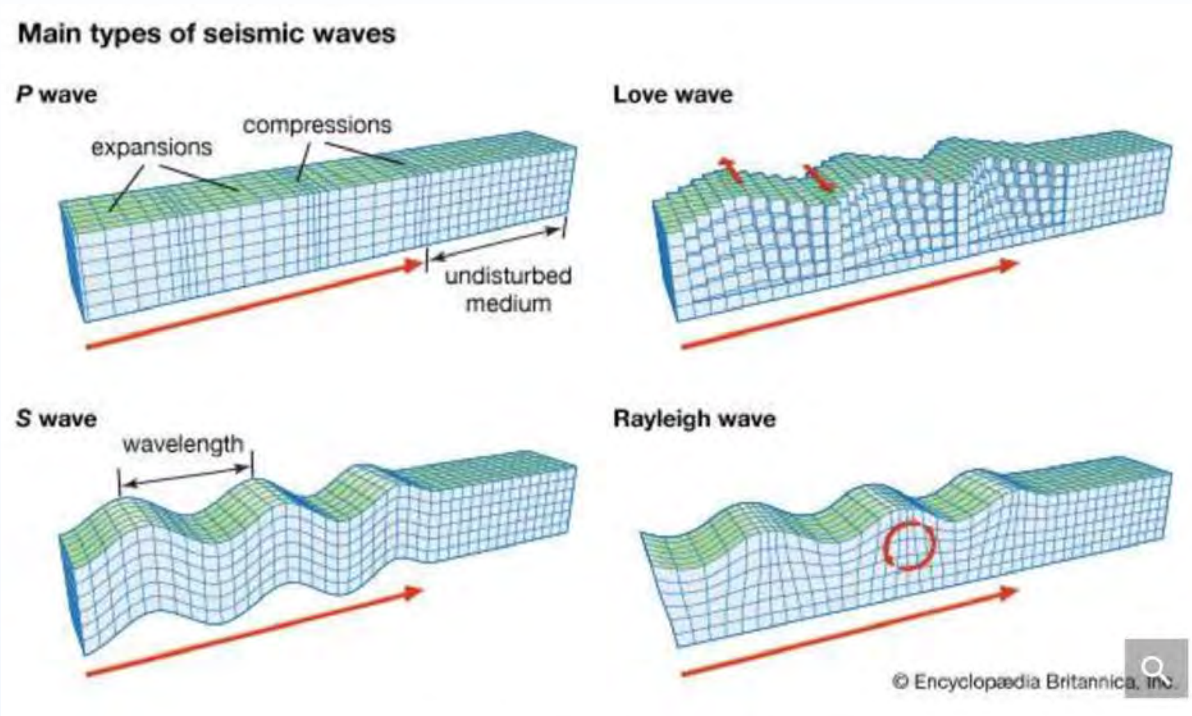


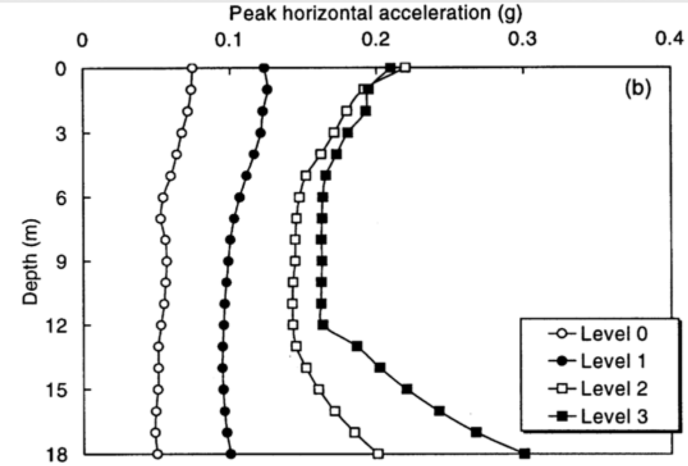
Earthquakes are one of the most severe threats for the sustainable development of the humankind

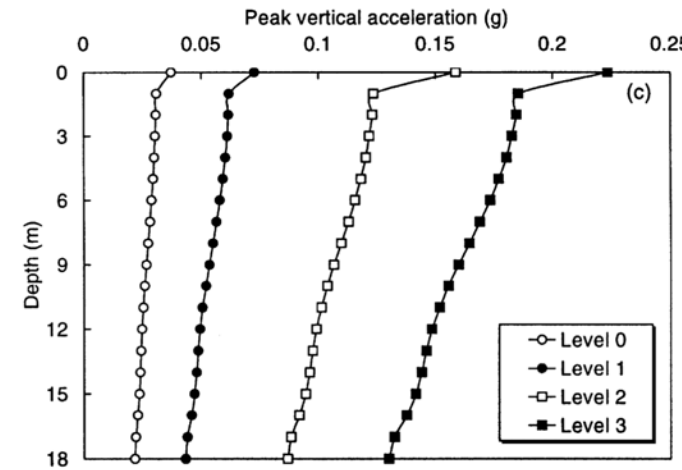
Our Mission: Protect buildings from collapsing

Our Goal: Provide the best earthquake dampers possible

Earthquake waves, displacements and the resulting accelerations



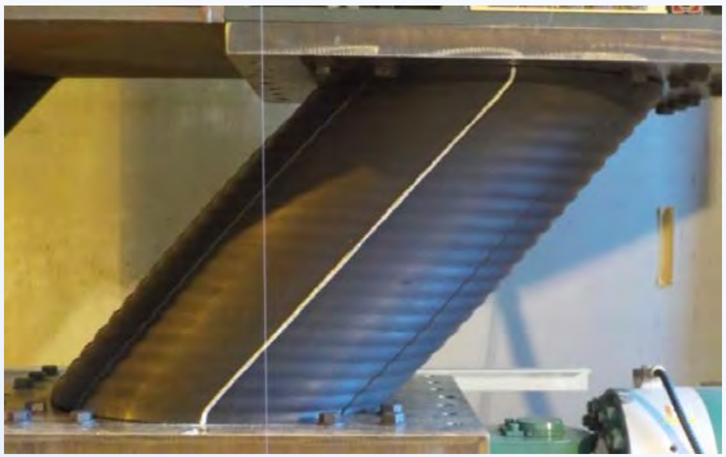


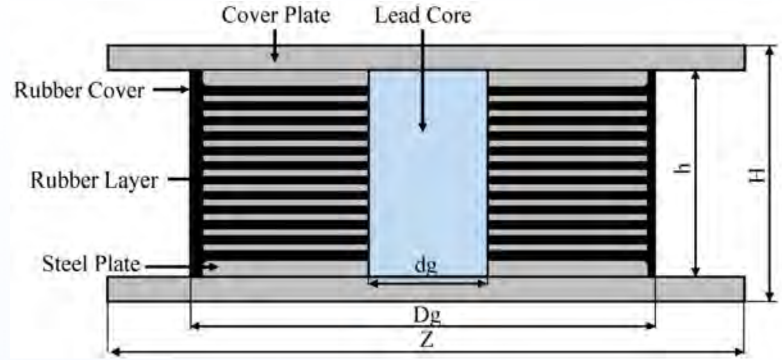


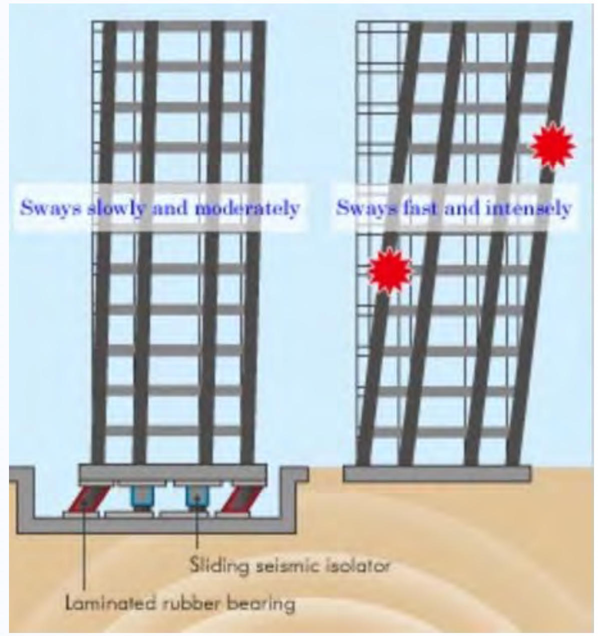
Horizontal and vertical accelerations are approximately of the same order of magnitude

J. Yang, T. Sato, S. Savidis, X.S. Li, Soil Dynamics and Earthquake Engineering, 22 (2002) 229-240.

Current earthquake dampers and their limitations







Current solutions do not damp vertical accelerations sufficiently!

Current railway isolation solutions and their limitations

Current solutions do not damp vertical loading sufficiently!

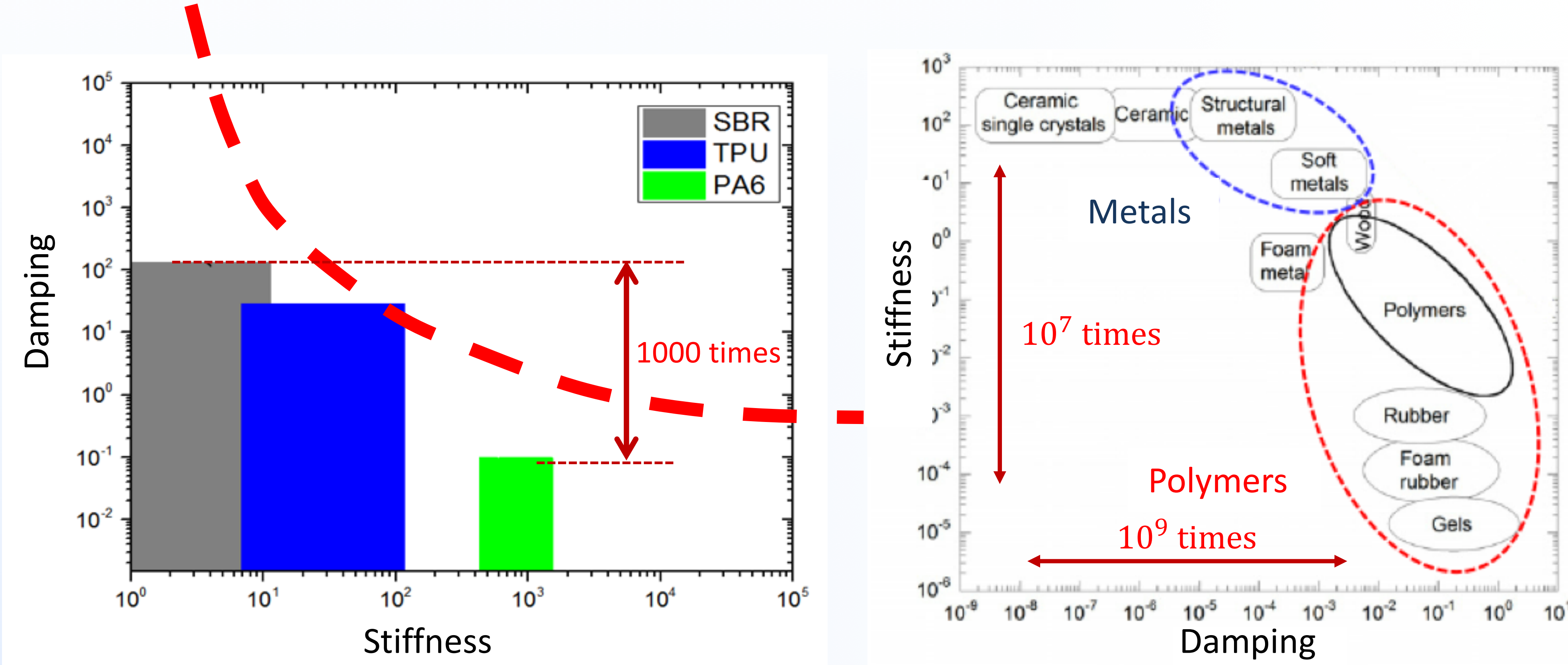
The new ultimate solution
Innovative Dampers

- We present the New Generation Damping Elements that exhibit orders of magnitude higher energy absorption than any existing solution.
- The new Earthquake Dampers are at least 10 -100 TIMES better than any existing solution! They can (almost) eliminate devastating effects of the earthquakes.
- Introducing the New Generation Damping Elements into the Great Silk Road railway transportation system will allow world-first cargo-trains traveling with speeds up to 400 km/hour!

HOW IS THIS POSSIBLE?

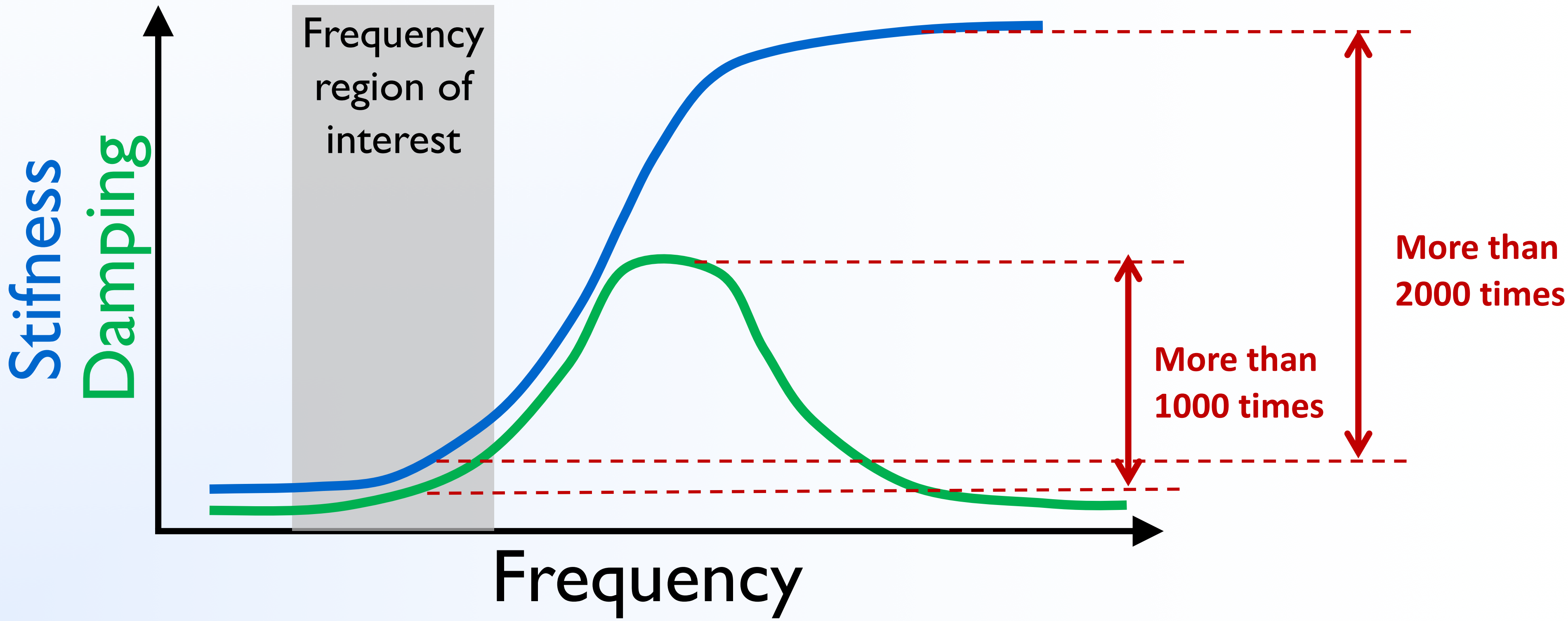
Limitations of the existing materials used for vibration and impact isolation

Application of the existing materials with high energy absorption is limited by their low modulus and consequently low stiffness.



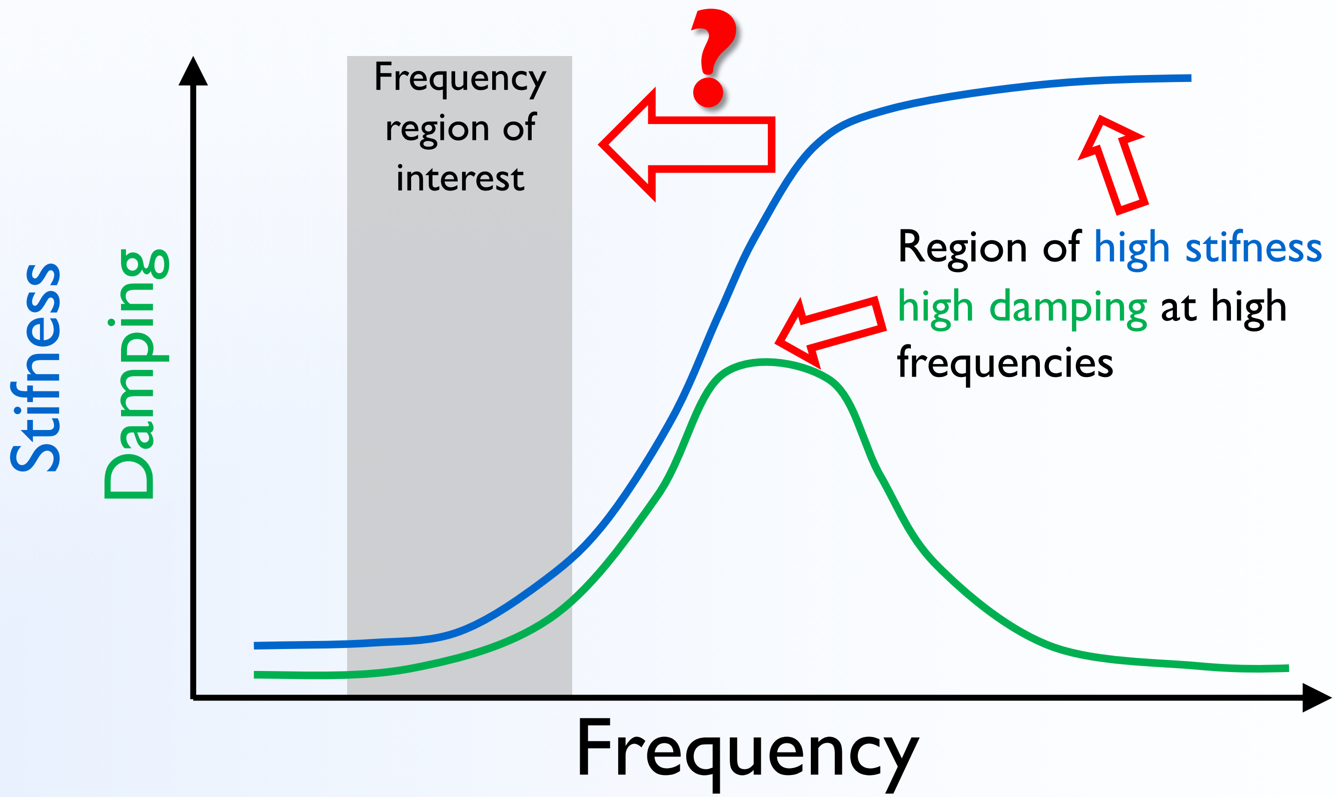
Frequency dependence of polymeric materials

- Mechanical properties of polymers are excitation frequency dependent.
- Polymers exhibit higher ”stiffness” and higher damping at higher frequencies

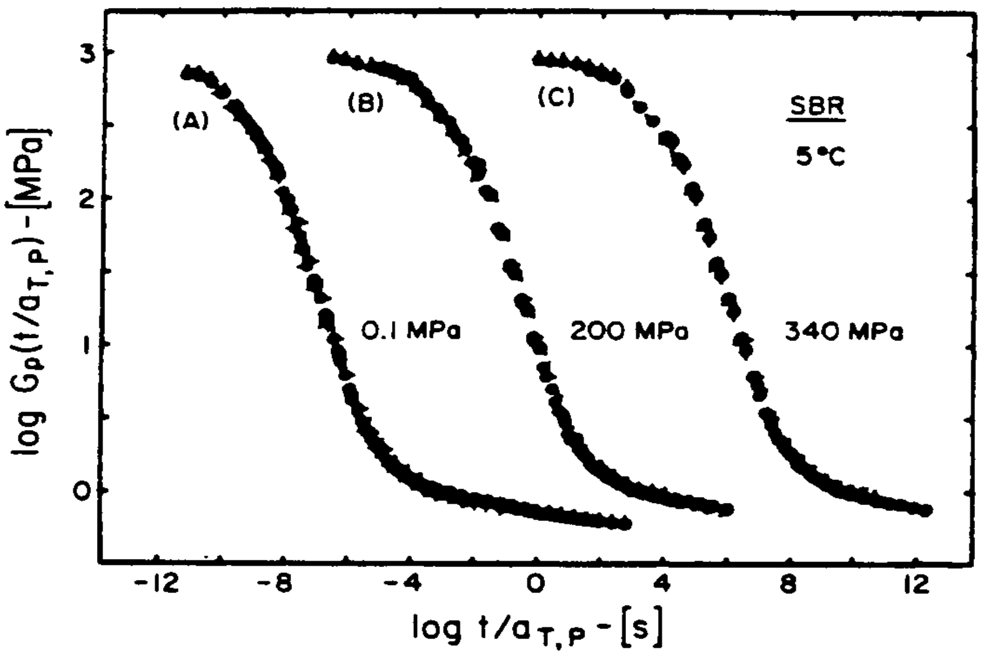


Frequency dependence of polymeric materials

- Is it possible to utilze full potentials of polymeric materilas?
- Is it possible to move properties at high frequencies to lower frequencies?



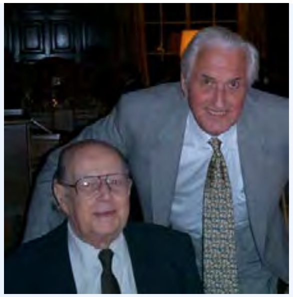
The Effect of Pressure (and Temperature) on time dependency of polymers



By exposing polymers to high hydrostatic pressure it is possible to modify their time and frequency dependence for several orders of magnitude.

Fillers-Moonan-Tschoegl, 1977, 1983.

$$\log a_{T,p} = -\frac{c_1^{rr}[T - T_{ref} - \theta(p)]}{c_2^{rr}(p) + T - T_{ref} - \theta(p)}$$

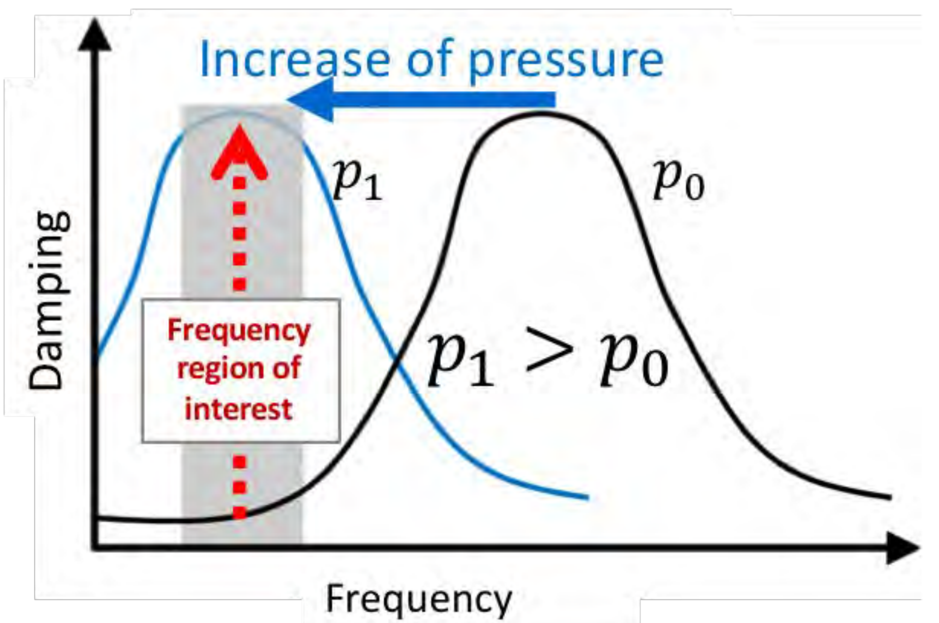


N.W. Tschoegl (left) and W.G. Knauss

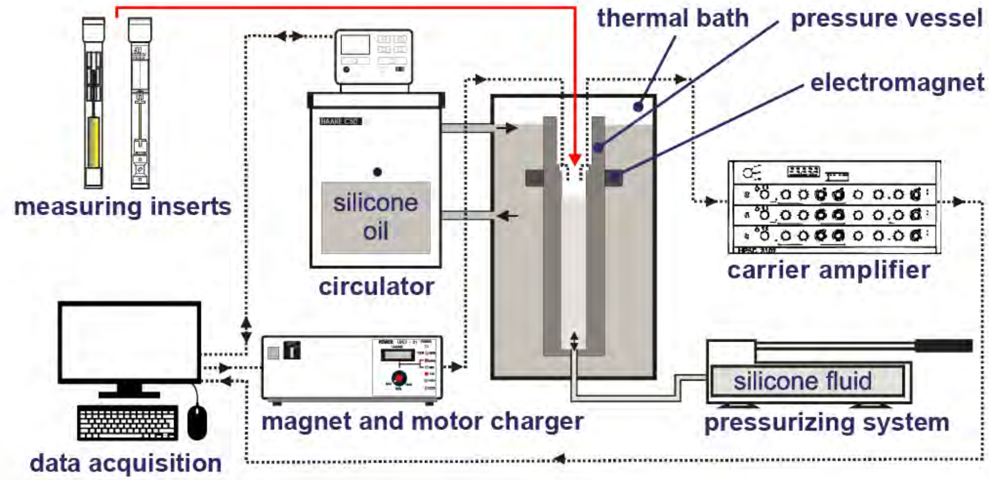
The FMT equation comprises the WLF equation. When $p = p_{ref}$ and $\theta(p) = 0$ the equation reduces to the WLF equation.

Our own research on the effect of pressure on damping of polymers

We have shown that by exposing polymers to hydrostatic pressure it is possible to bring energy absorption maximum to any desired frequency.



Our unique measuring system



- The effect of temperature and pressure on the mechanical properties of thermo-and/or piezorheologically simple polymeric materials in thermodynamic equilibrium–A critical review; *Mechanics of Time-Dependent Materials* 6 (1), 53-99, 2002
- Poisson's ratio in linear viscoelasticity–a critical review; *Mechanics of Time-Dependent Materials* 6 (1), 3-51, 2002
- A measuring system for bulk and shear characterization of polymers; *Experimental mechanics* 46 (4), 429-439, 2006
- The closed form tTP shifting (CFS) algorithm; *Journal of rheology* 55 (1), 1-16, 2011 **The New ISO STANDARD: ISO 18437: 2017**

Our own research on the effect of pressure on damping of polymers

Knauss-Emri model for modelling the effect of pressure on earthquake isolation stiffness and damping.

$$\sigma_{kk}(t) = 3\int_0^t K[t'(t) - \lambda'(t)] \frac{\partial \theta(\lambda)}{\partial \lambda} d\lambda \qquad S_{ij}(t) = 2\int_0^t G[t'(t) - \lambda'(t)] \frac{\partial e_{ij}(\lambda)}{\partial \lambda} d\lambda$$

$$t'(t) - \lambda'(t) = \int_\lambda^t \frac{d\xi}{\Phi[T(\xi), \theta(t), c(\xi)]} \qquad \log \Phi[T(\xi), \theta(t), c(\xi)] = \frac{b}{2.303}\left(\frac{1}{f[T(\xi), \theta(t), c(\xi)]} - \frac{1}{f_0} \right)$$

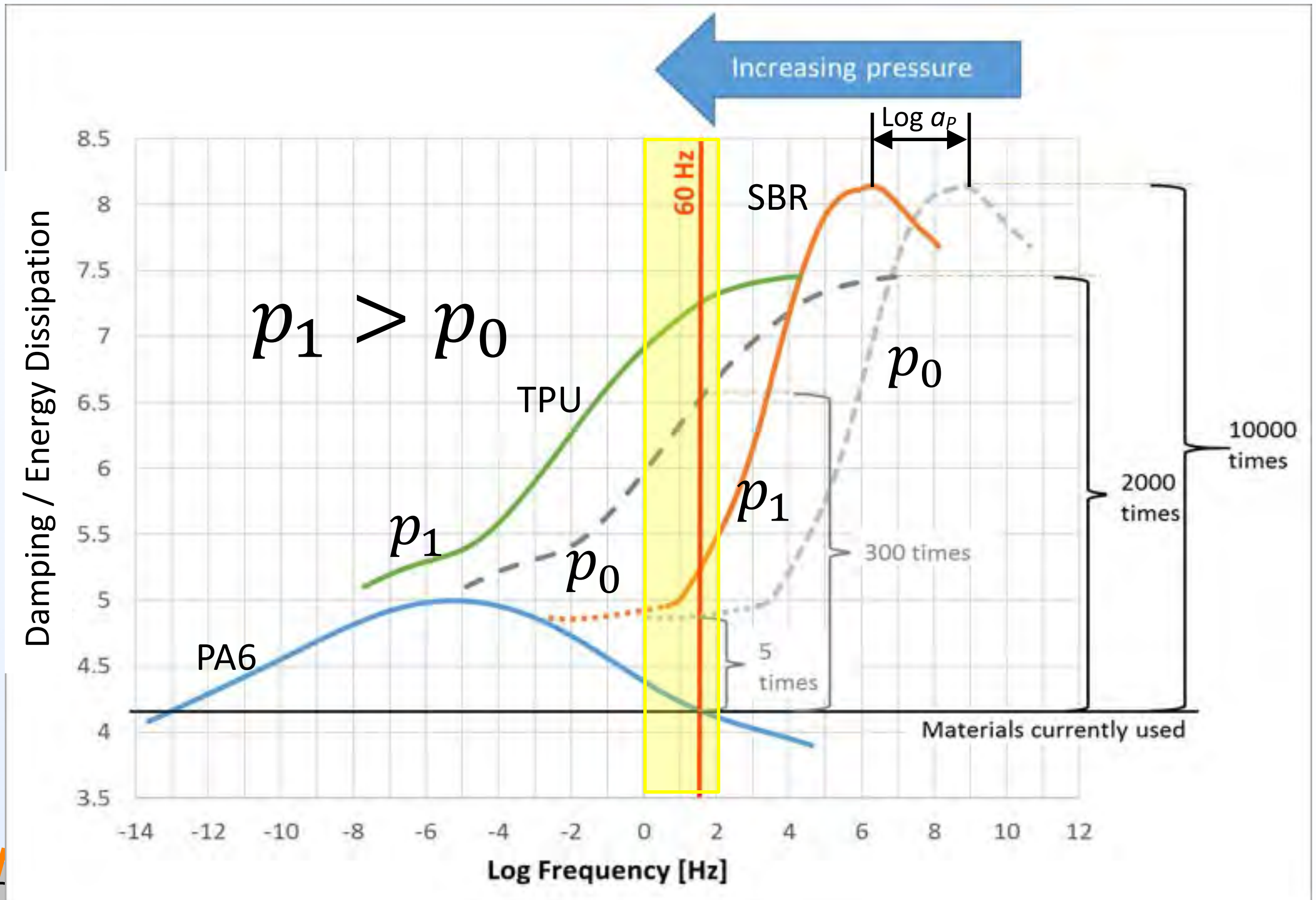
$$f[T(\xi), \theta(t), c(\xi)] = f_0 + f_T + f_\theta + f_c$$

$$f_T = \int_0^t \alpha(t-\lambda) \frac{\partial T(\lambda)}{\partial \lambda} d\lambda \qquad f_\theta = \frac{1}{3}\int_0^t M(t-\lambda) \frac{\partial \sigma_{kk}(\lambda)}{\partial \lambda} d\lambda \qquad f_c = \frac{1}{3}\int_0^t \gamma(t-\lambda) \frac{\partial c(\lambda)}{\partial \lambda} d\lambda$$

- Volume change and the nonlinearly thermo-viscoelastic constitution of polymers; *Polymer Engineering & Science 27 (1), 86-100, 1987*
- Non-linear viscoelasticity based on free volume consideration; *Computers & Structures* 13 (1-3), 123-128, 1981

Ultimate Vibration Insulation:
Innovative solution

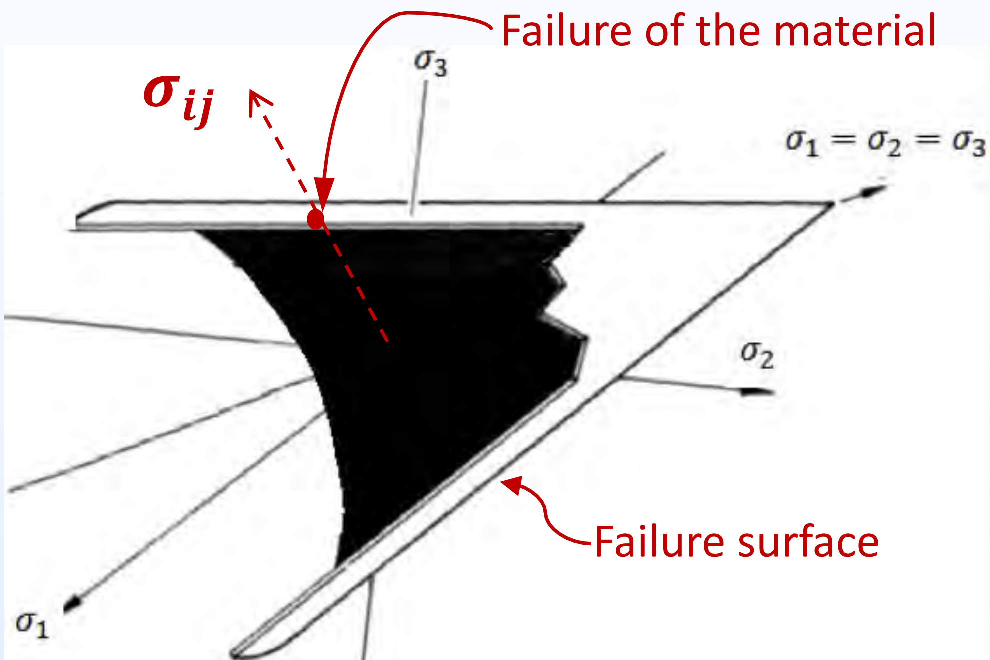
By exposing polymers to hydrostatic pressure one can change their frequency dependence and **improve material damping properties by orders of magnitude**.



$$\log a_P = \frac{c_1 \theta(P)}{c_2 - \theta(P)}$$

How to generate high hydrostatic pressure?

High hydrostatic pressure $P = \sigma_1 + \sigma_2 + \sigma_3$ cannot be achieved through **simple uniaxial compression** because of the presence of shear stresses, which destroy the material before the pressure that modifies its properties is reached!



On micro- in nano-scale bulk properties dominate over shear

→ One can generate high hydrostatic pressure by using granular materials!

$$\lim_{V \to 0} \frac{\sigma_{kk}}{\tau_{ij}} = \infty$$

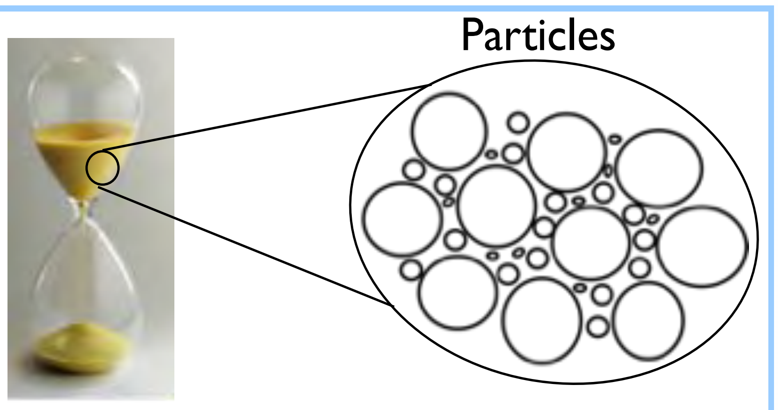
- Mechanics of polymers: Viscoelasticity; *Springer handbook of experimental solid mechanics*, 49-96, 2008
- Rheology of solid polymers; *Rheology Reviews* 2005,
- Time-dependent behaviour of solid polymers; *Encyclopaedia of life support systems (EOLSS), UNESCO*, 2010
- Textbook: Statics – Learning Statics: Learning from Engineering Examples, Springer, 2016

Behavior of granular materials - 1

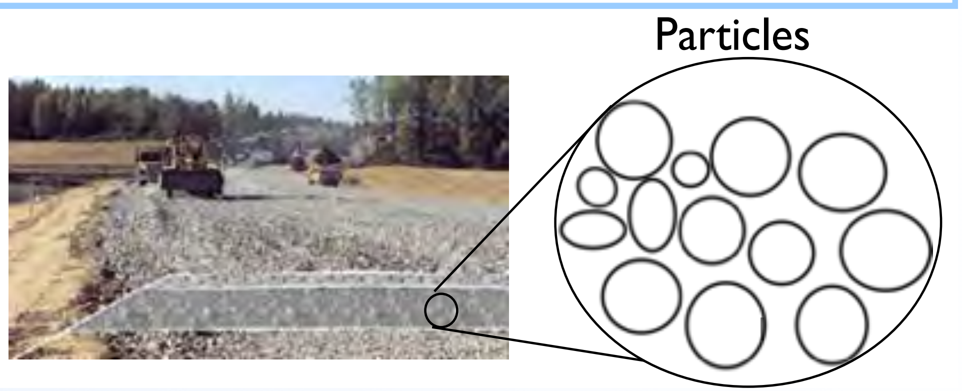
We use granular materials to generate 3D (hydrostatic) pressure :

- Granular systems may exhibit **fluid-like behavior** when proper particles size distribution is selected.

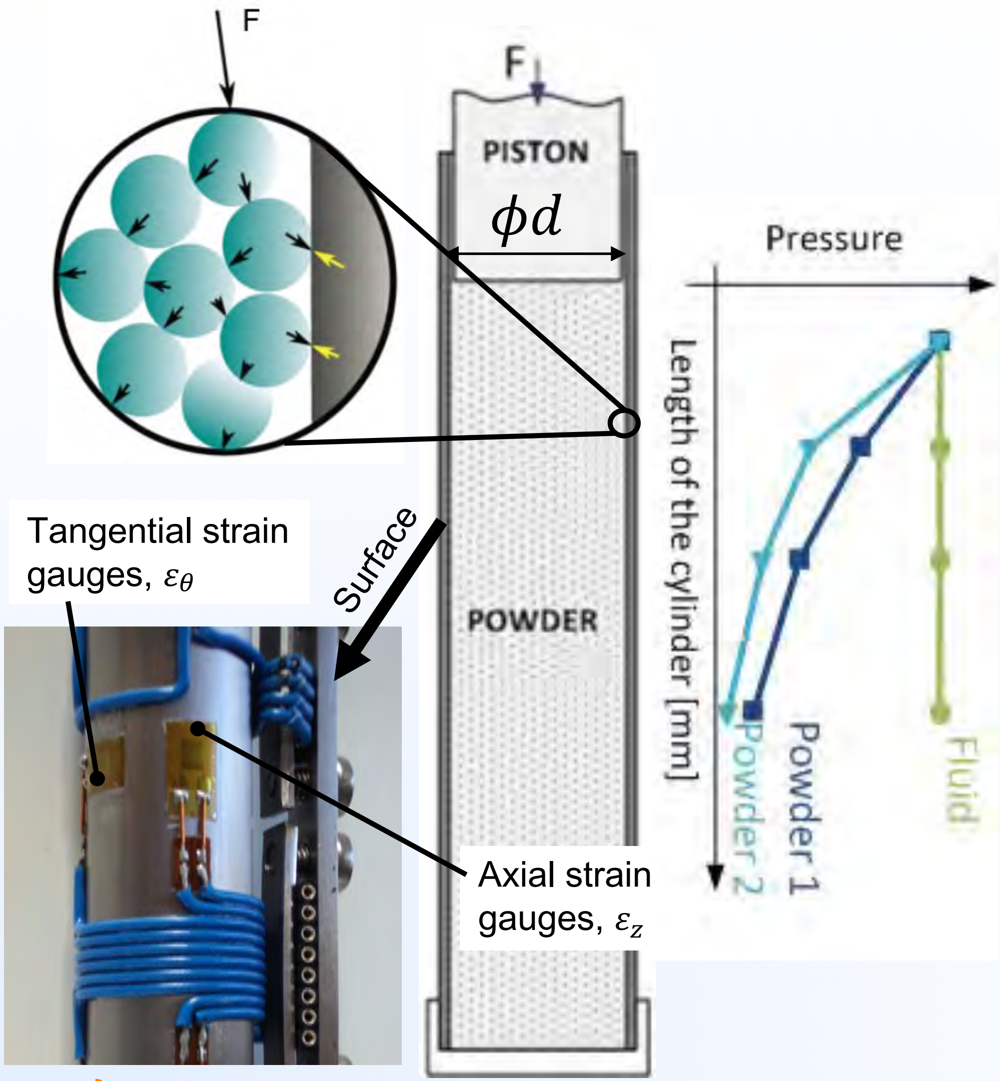
Fluid-like behavior



Self-locking behavior



Concept of the Granulate Flow Analyzer (GFA) apparatus



We have developed the new measuring system to study flowability of granular materials:

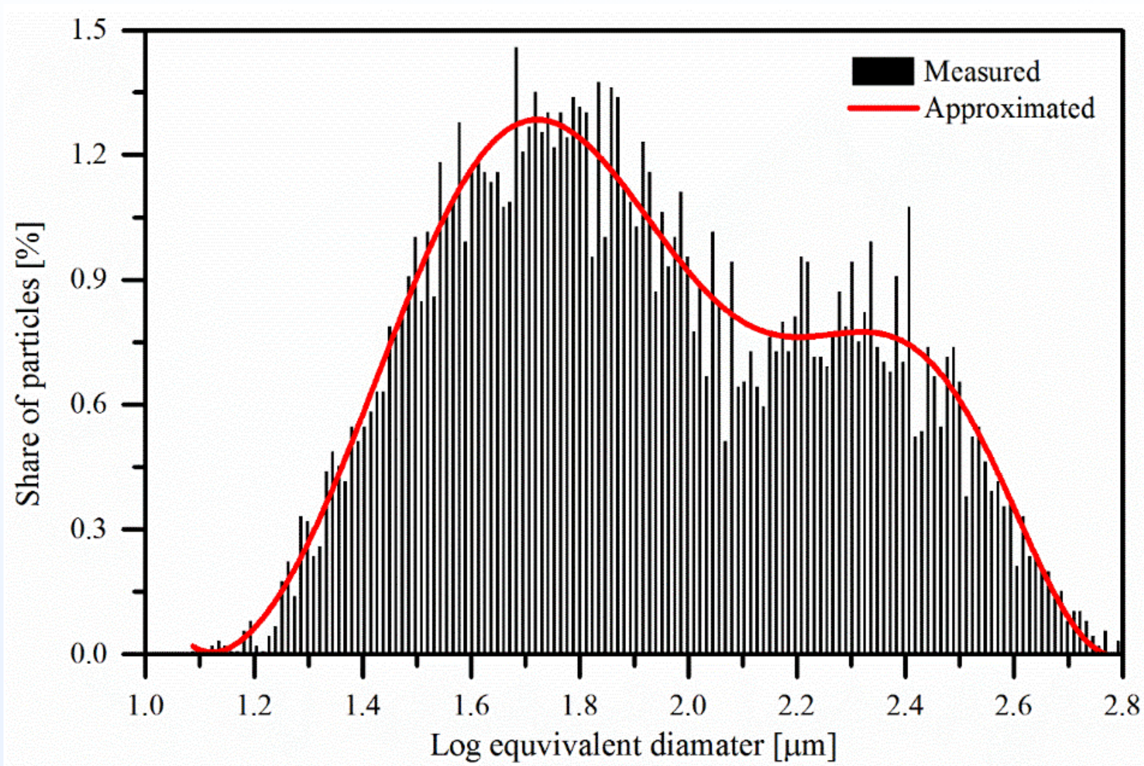
- Cylinder - filled with granular material - force applied on top by piston
- Confined compression of granular material inside a cylinder leads to an elastic deformation of cylinder
- Strains are measured by strain gages on the surface of the cylinder
- Strain gauges in axial ε_z and tangential directions ε_θ

M. Bek, J. Gonzalez-Gutierrez, J. A. M. Lopez, D. Bregant, and I. Emri, *Powder Technology* 288, 255 (2016).

Optimized particles size-distribution to generate fluid-like hydrostatic pressure

Proper selection of particles size-distribution will lead to material fluid-like behavior

→ **Granular material flows like water!**



M. Bizjak: The Effect of Granular Rubber Size Distribution On Their Fluidity. Master Thesis, Faculty of Mechanical Engineering, University of Ljubljana, 2013

Inventive patented idea – Research-based Invention

Patent EP2700839 (2016): "Dissipative bulk and granular systems technology,"

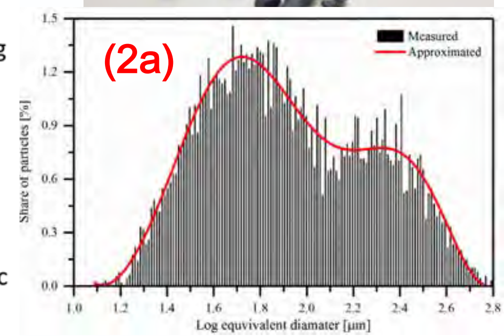
- By using a proper size-distribution of granular materilas we may control their "readiness to flow", i.e., they mimic ***fluid-like*** **(watter-like)** behavior.
- We use such granular material to generate hydrostatic pressure within a flexible rigid container – Similarly as we generate pressure within automobile tires.
- Granular material acts as a pressurizing media and, at the same time, it imposes hydrostatic pressure on itself and changes its own (damping) properties!
- **By modifying hydrostatic pressure we can adjust location of the material maximal energy dissipation to any desired frequency!**

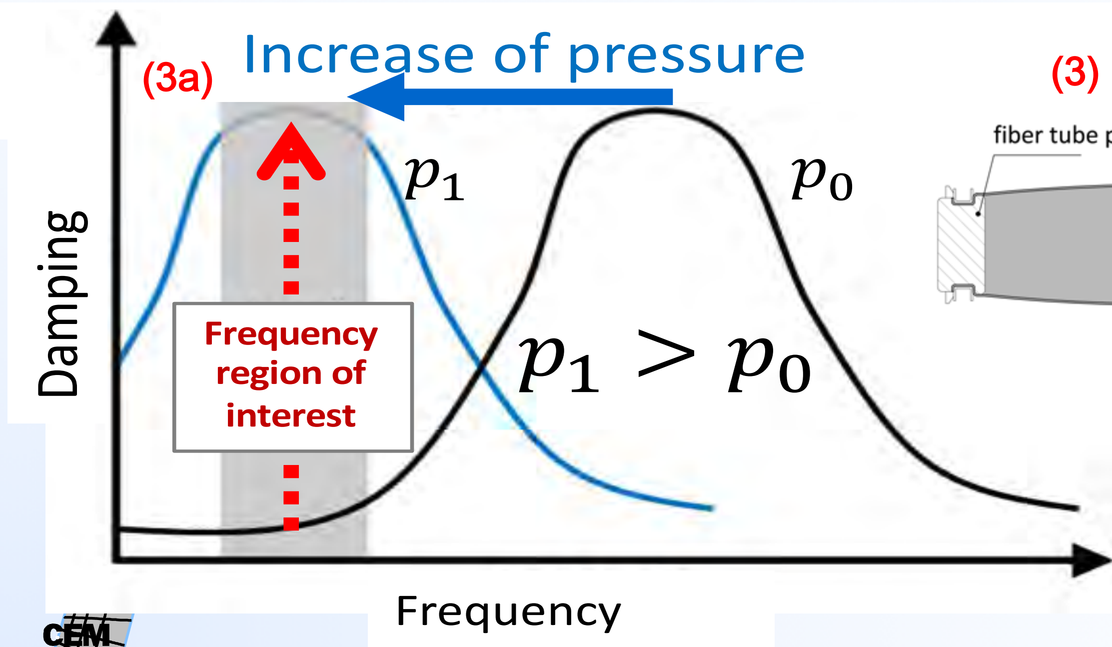
→ We obtain the isolation with ultimate (best) damping/energy absorption priperties!

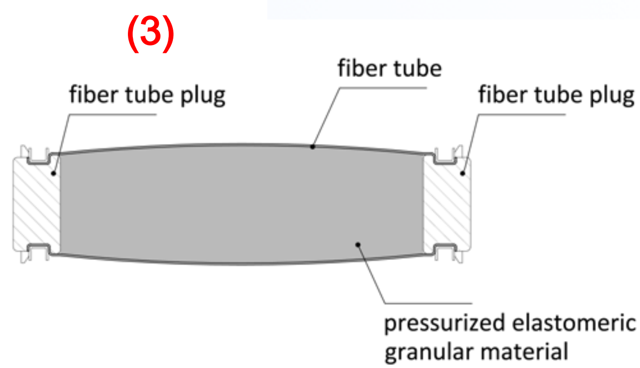
Patented Technology and the Granular Damping Elements- GDE

Structure of the Granular Damping Element (GDE):

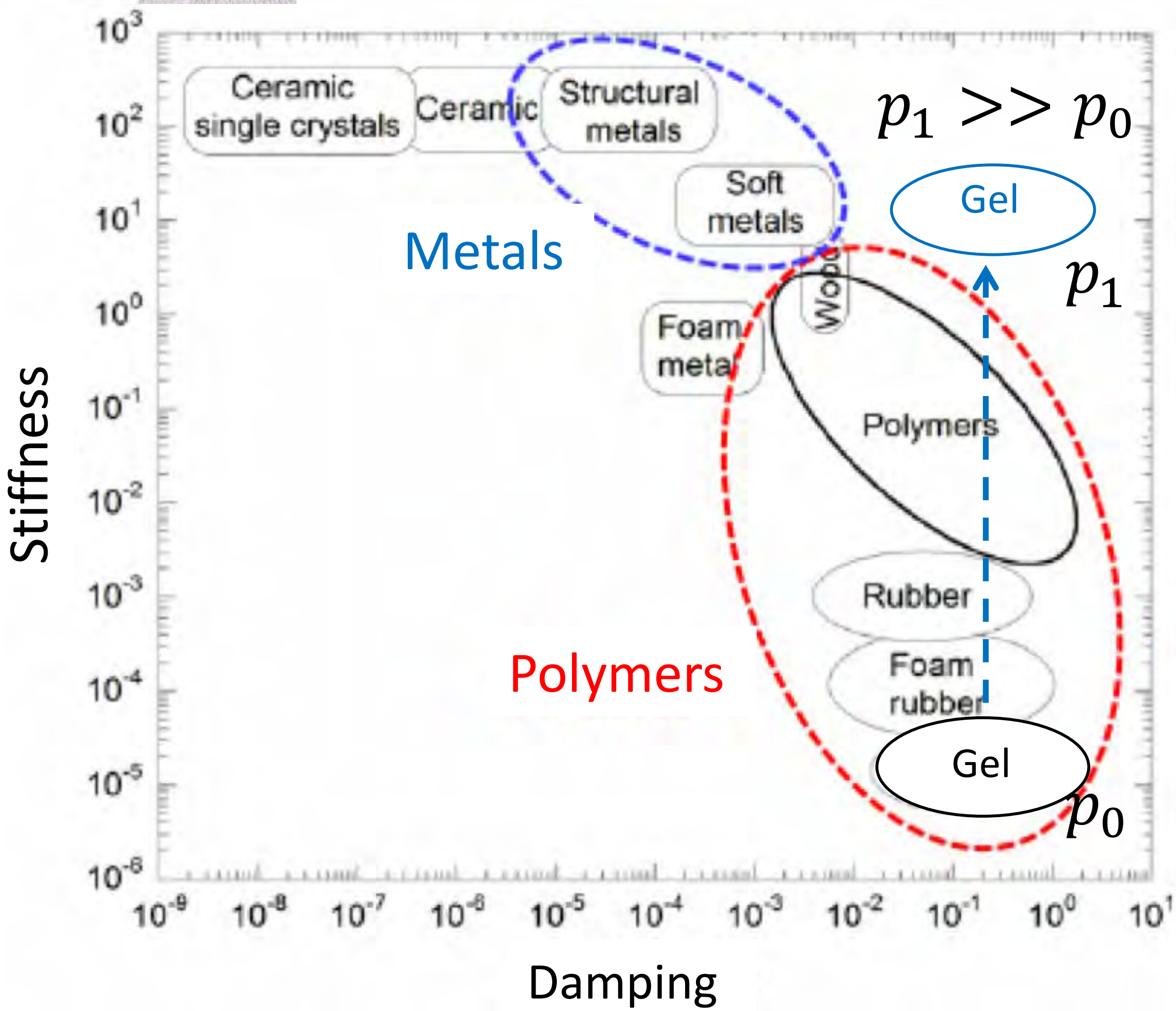
1) Woven bazalt and/or carbon fibers tube.
2) Filled with multimodal granular polimeric (elastomeric) material with fluid-like behavior.
3) With self-presurization we adjust material frequency-dependent damping properires to a desired frequency.







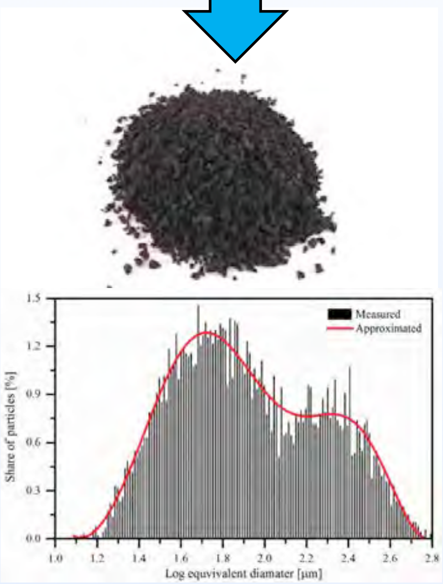
The new ultimate GDE earthquake isolation with unmatched properties



By using the newly developed high pressure technology we can produce dampers with high energy absorption and high stiffness, where both properties may be adjusted independently.

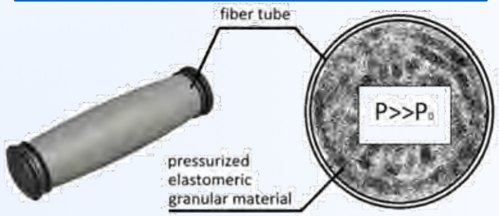
Green solution for Safer world against earthquakes

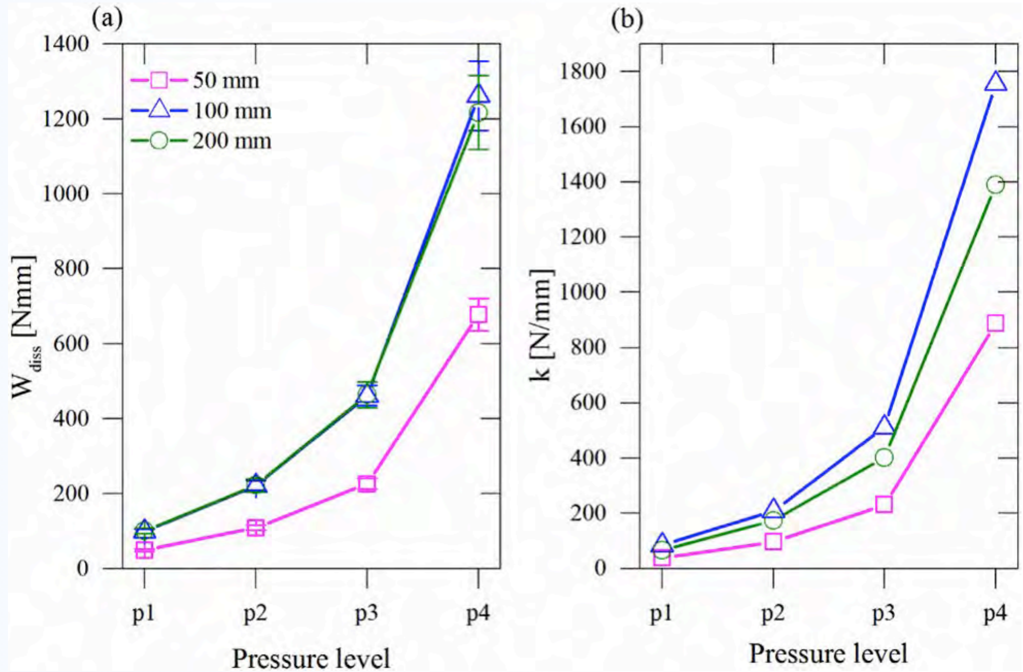
Waste tires rubber



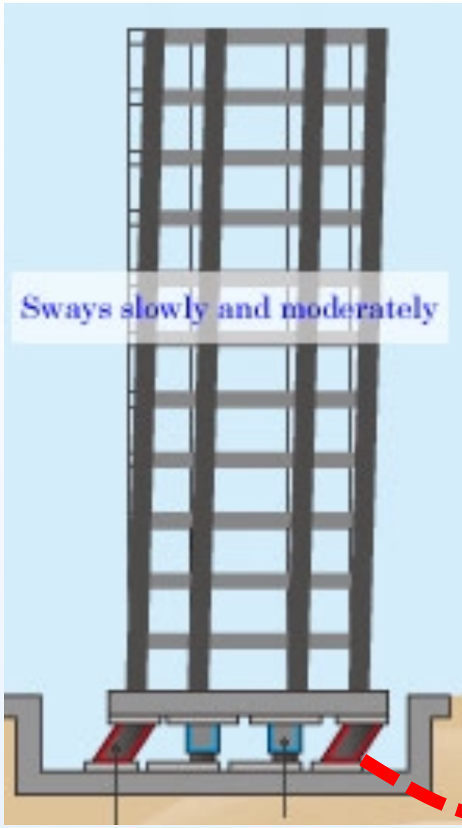
- Energy absorption W_{diss}, and stiffness k, of the damping element is increased by exposing grinded waste tires rubber to selected hydrostatic pressure.
- At hydrostatic pressure p4 energy absorption was increased **12 TIMES** and stiffness **20 TIMES!**
- With higher pressures further improvements are possible.

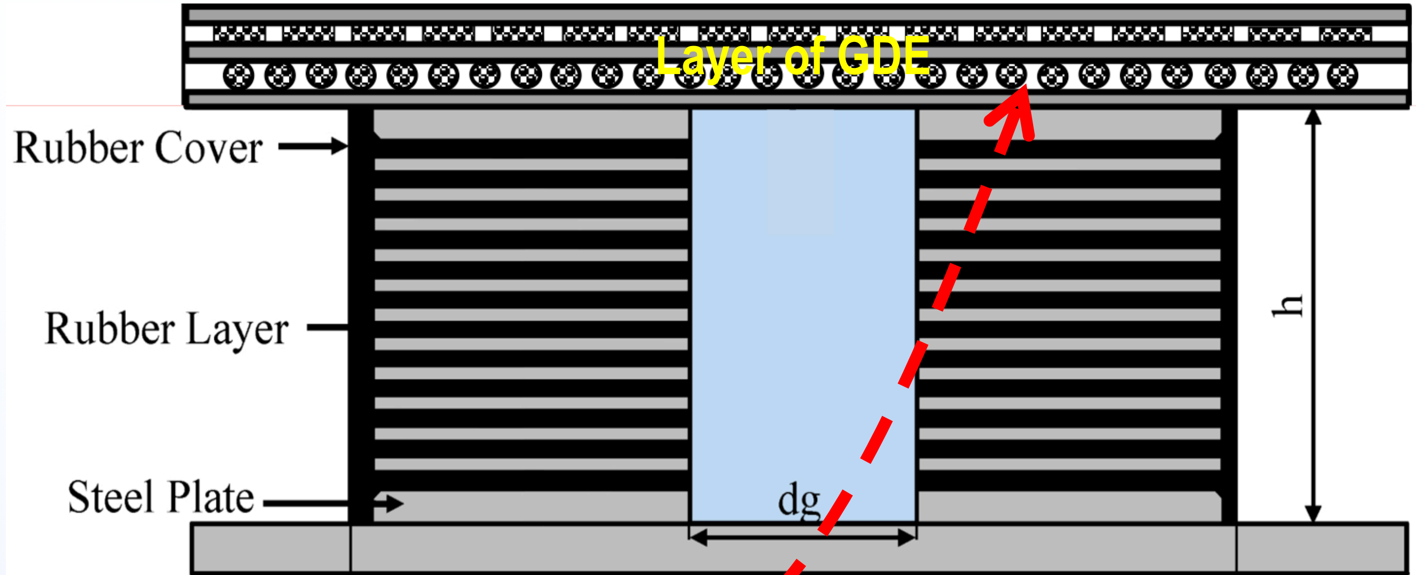
GDE
Granular damping element





Upgrading the existing earthquake solutions with the GDE



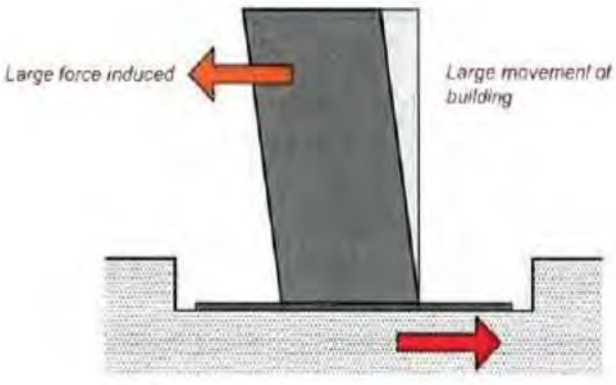


By introducing layers of the new GDE damping elements vertical forces acting on a building **will be reduced 10 – 100 times**!

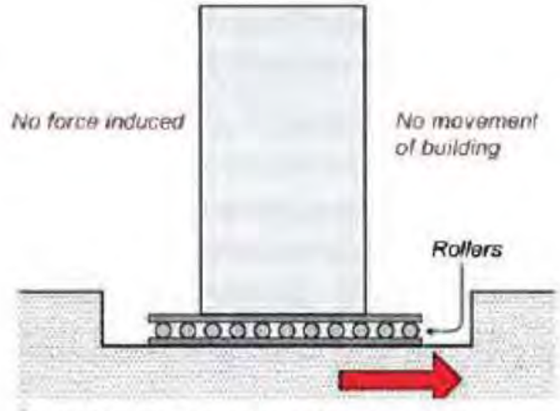
Upgrading the existing solutions with the new ultimate GDE vibration isolation for the high-speed (cargo) trains

By replacing the existing damping elements between the two concrete plates with the new GDE damping elements the **vibration-isolation will be improved 10 – 100 times,** allowing transportation of the cargo-trains up to 400 km/hour!

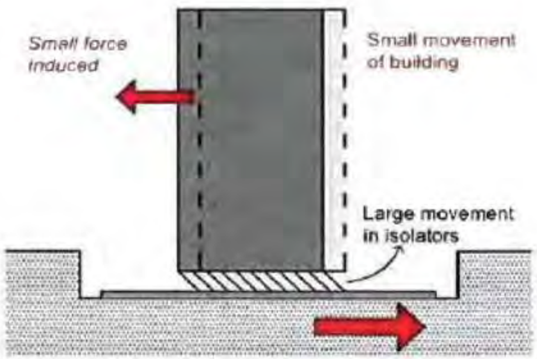
Limitations of the existing earthquake solutions

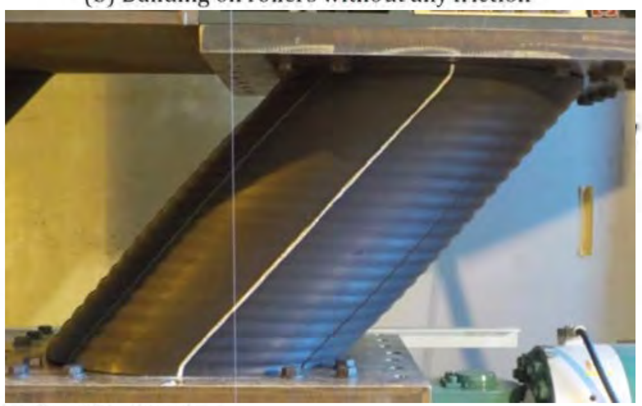


(a) Building resting directly on ground



(b) Building on rollers without any friction





(c) Building base isolated with lead- rubber bearing.

Hosseini et al., J Archit Eng Tech 2017, 6:1

Safety issues:

- Allowable maximal ground motion is limited with the height of the isolation, which is limited with its stability.
- Building is still exposed to horizontal dynamic forces generated by the isolation – problems with building resonance.

→ At more severe earthquakes buildings will still collapse!

Affordability issues:

- Existing solutions are very expensive.

New affordable GDE-based isolation with ultimate performance

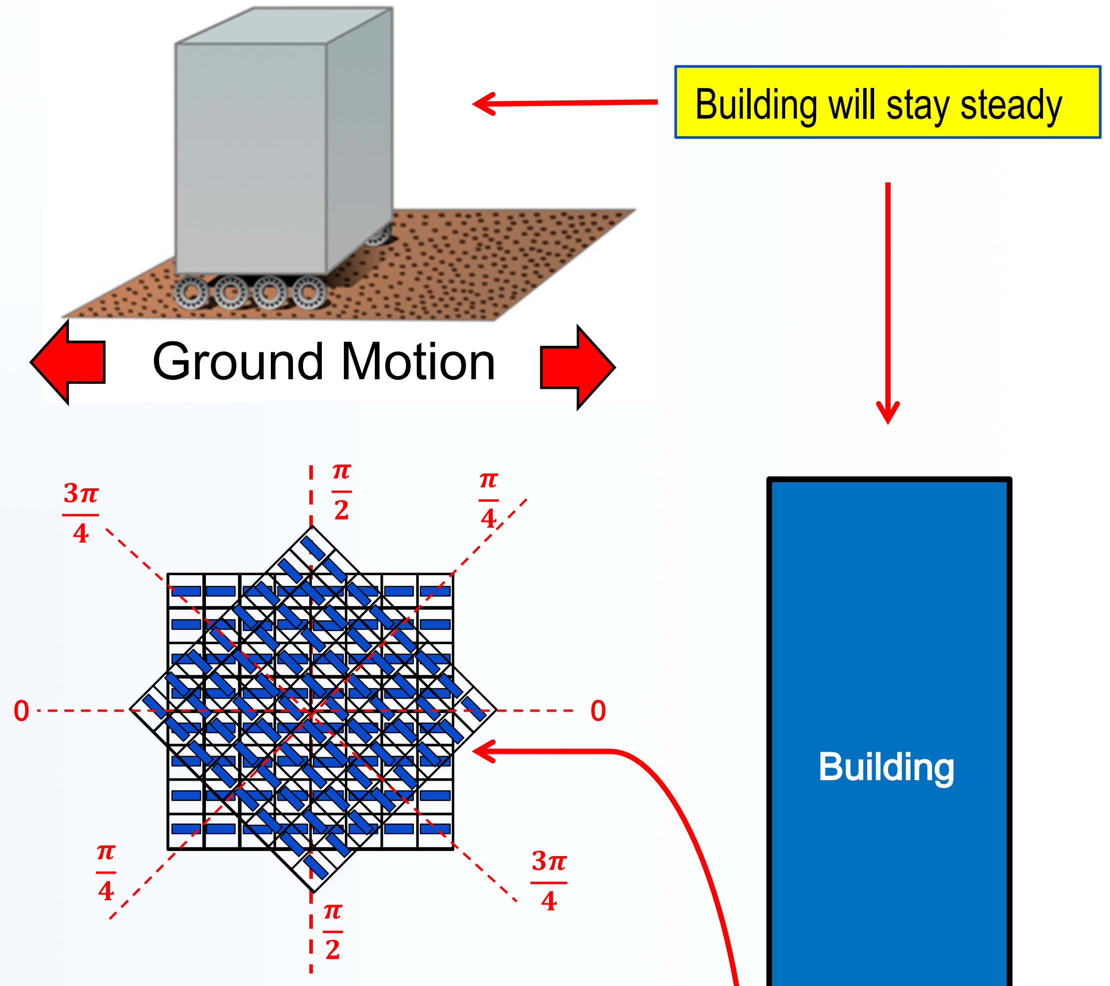
Handling of the horizontal motion of the ground:

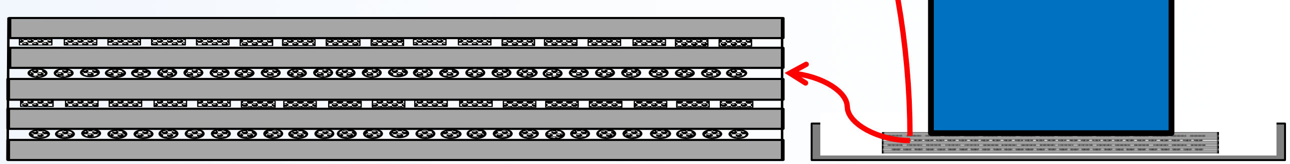
- Basic unit of the GDE is a “roller”.
- With pre-pressurization of GDE one can control the rolling friction.
- Four layers of DGE rollers separated by prestressed concrete plates.

→ Horizontal ground motion may be arbitrarily large

Handling vertical motion of the ground:

- Four (or more) layers of DGE will reduce vertical accelerations to almost any required (allowable) level.





Conclusion – Our current achievements

Breakthrough inventions and research findings:

- **Breakthrough inventions**
  - Approach for utilization of the full materials damping potential
  - Specific granular size distribution to combine solid-state and fluid-state material properties
- **Found and needed research fundamentals**
  - Viscoelastic material characterization with unique high-pressure measuring system
    - in search for highest damping potential
    - in search for suitable pressure sensitivity
  - Relaxation experiments under high pressure
  - Closed-form-shifting algorithm for unbiased master-curve creation
  - Interconversion between time- and frequency- domain using mechanical spectrum
  - Emri-Tschoegl Algorithm for determination of mechanical spectrum.
  - Knauss-Emri model for modelling the effect of pressure

Next steps to large scale earthquake protection

Necessary steps to perform large scale earthquake tests

- Design and build full scale damper prototypes for earthquake application
- Increase pressure in damping elements up to 1000 bar
- Multiply prototypes/develop mass-production scheme
- Select recognized earthquake testing laboratory (in Europe, Taiwan, California)
- Perform standardized earthquake simulation tests

- Raise R&D funding → **acquire venture capital**

HVALA ZA POZORNOST