Earthquakes, Geohazards, and Real-Time Remote Monitoring of Onshore and Offshore Gas Pipelines

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Short biography

Studies (at NTUA):

- 1994 BEng & MEng in Civil Engineering
- 1999 MSc in Structural Engineering
- 2001 PhD in Geotechnical (Earthquake) Engineering

Professional experience (since 1994)

Involvement in the design (and construction) of various challenging engineering projects in Greece and abroad as a Geotechnical & Earthquake Engineering Consultant

Scientific experience (since 2001)

- Postdoctoral researcher in Greece and Italy (POLIMI & EUCENTRE)
- Various academic positions in Greece (NTUA, HAFA)
- More than 30 publications in scientific journals and books
- More than 150 publications in conference proceedings

Personal involvement in the design of oil & gas projects

1. Seismic design of the upgrade of the main oil refinery in Elefsina, Greece
   (contribution to the Final Design with NKUA & NTUA)

satellite view
of the pre-existing refinery
and the area of the upgrade

view
of the upgraded refinery
during the construction phase

Personal involvement in the design of oil & gas projects

2. Quantitative geohazard assessment and seismic design of the Greek onshore part and the landfall of Italy – Greece Interconnector (IGI) – Poseidon
(lead expert of the FEED)

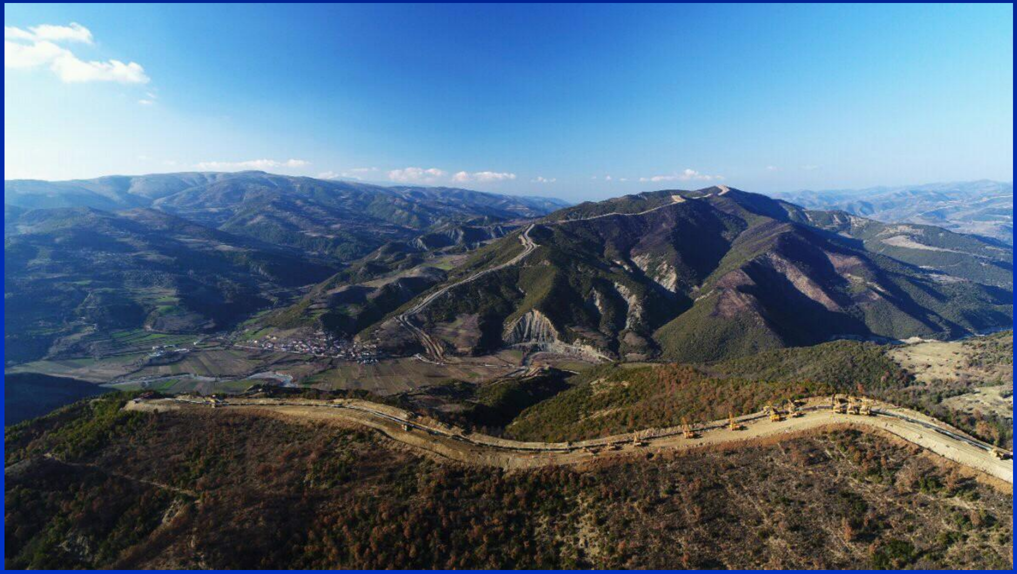
sketch showing IGI-Poseidon that is expected to connect Greece with Italy

the landfall area of IGI-Poseidon

Personal involvement in the design of oil & gas projects

3. Quantitative geohazard assessment and seismic design of all onshore parts of Trans Adriatic Pipeline (TAP) (770 km in Greece, Albania, and Italy)
   (one of the lead experts of the FEED)

sketch showing TAP routing
(part of the Southern Gas Corridor)



TAP pipeline in Albania
during the construction phase
(courtesy: Spiegapac)

Personal involvement in the design of oil & gas projects

4. Qualitative geohazard assessment of the EastMed pipeline (contribution to ESIA study)

(a) onshore and offshore parts of EastMed pipeline, and
(b) the prevailing conditions in SE Mediterranean
(i.e., deep waters, tectonic activity, high seismicity)

Motivation

1. In our modern society, risk assessment and management of onshore and offshore gas pipelines is an issue of paramount importance

2. Various gas pipelines are constructed in harsh environments (onshore, offshore, or nearshore)

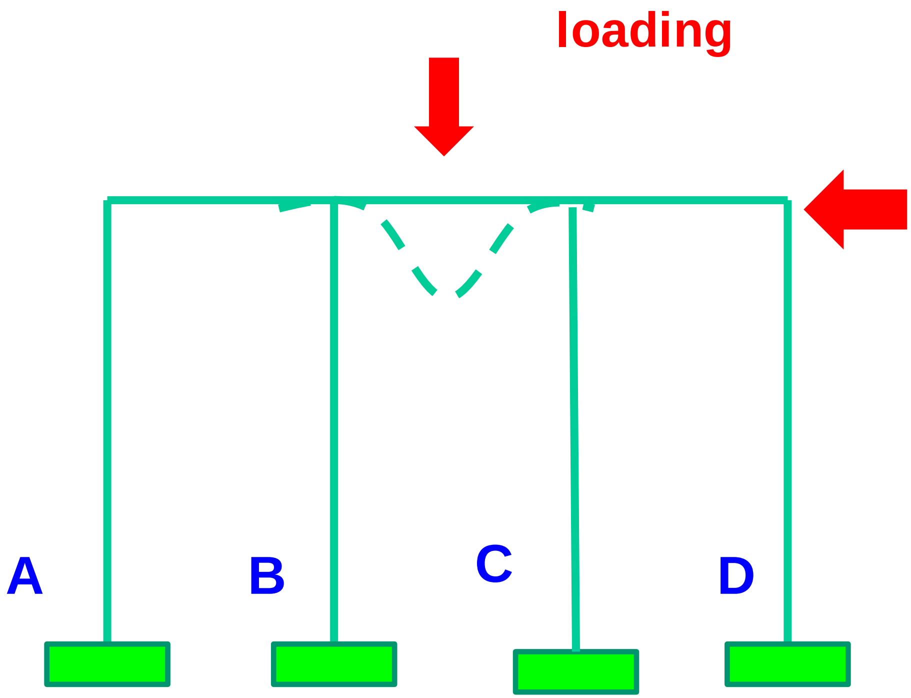
3. Geohazards, including earthquake-related geohazards, are serious threats for any gas pipeline

4. For various reasons real-time remote monitoring is a powerful tool to minimize the risk of a pipeline

Structural distress

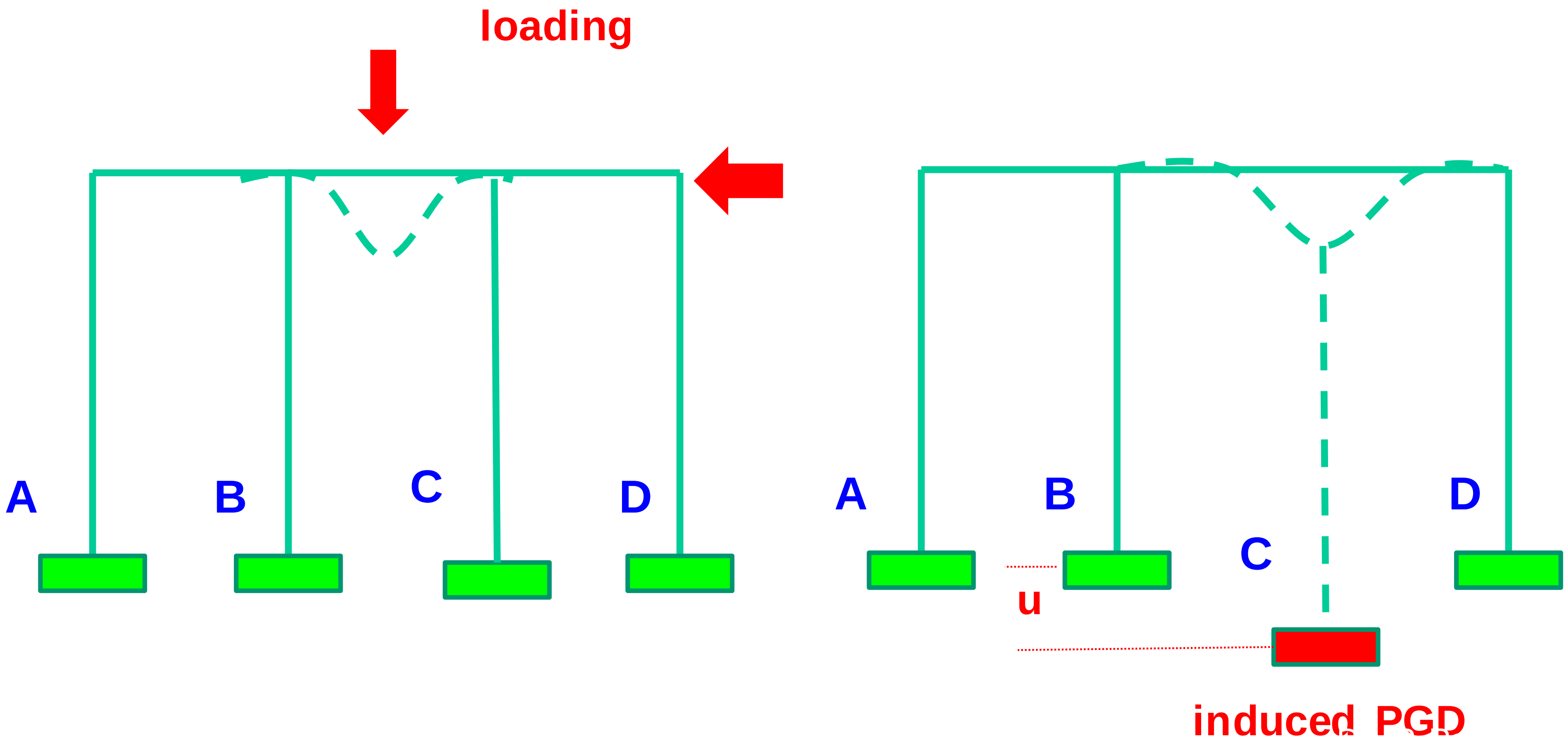
All structures (including pipelines) may be distressed by:

a) static and dynamic (external or internal) loading



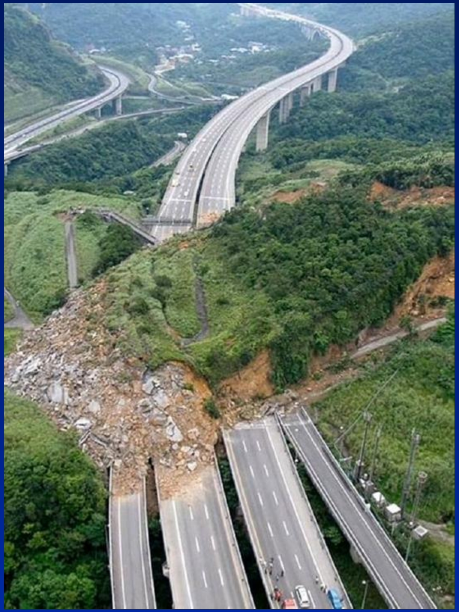
Structural distress

All structures (including pipelines) may be distressed by:
a) static and dynamic (external or internal) loading, and/or
b) induced permanent ground displacements (PGDs)



Onshore geohazards
under static conditions

special soils (turf) in Greece



landslide in Taiwan

erosion in Israel

rockfall in Greece

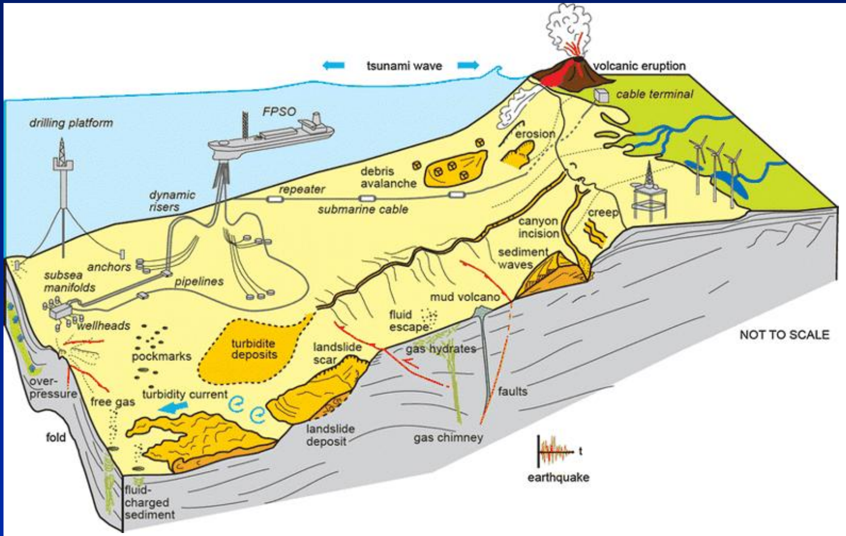
Vulnerability of gas pipelines

Failures due to ground movements (i.e. landslides)

Explosion and fire at
the Sabah-Sarawak Gas Pipeline (SSGP) in Malaysia in 2014.
Note: SSGP has already four incidents related to landslides.

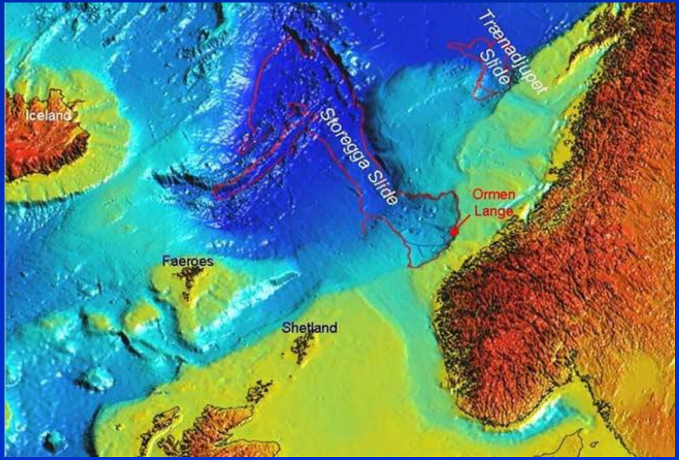
Offshore or near-shore geohazards

under static conditions



- **submarine landslides**
- **shallow gas**
- **dissociation of gas hydrates**
- **shallow water flow**
- **mud volcanoes**

(after Chiocci et al., 2011)

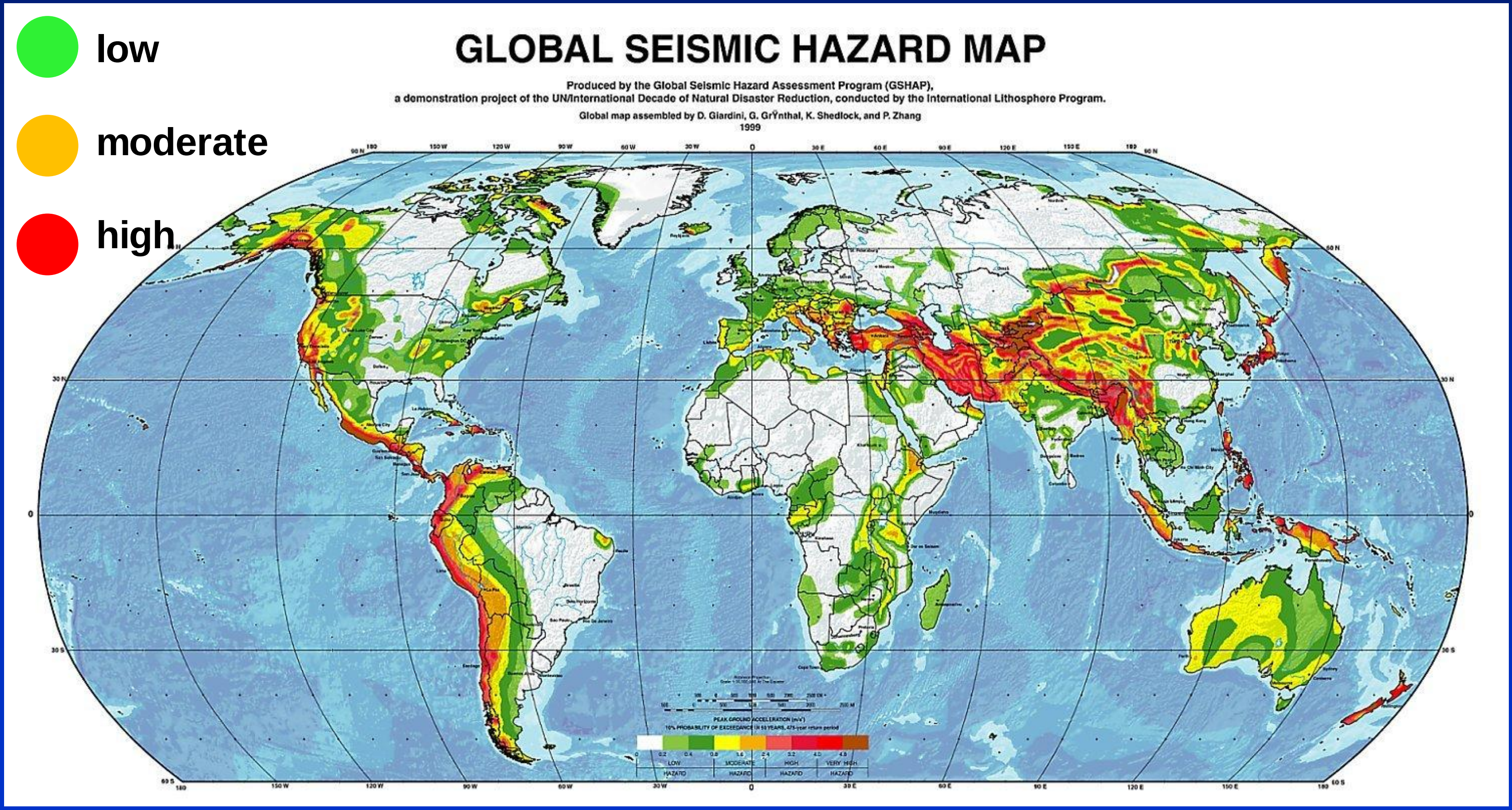


Submarine landslide in North Sea
(after Kvalstad et al., 2005)

Near-shore landslide
on the Isle of Wight (UK)

Seismicity and structural distress

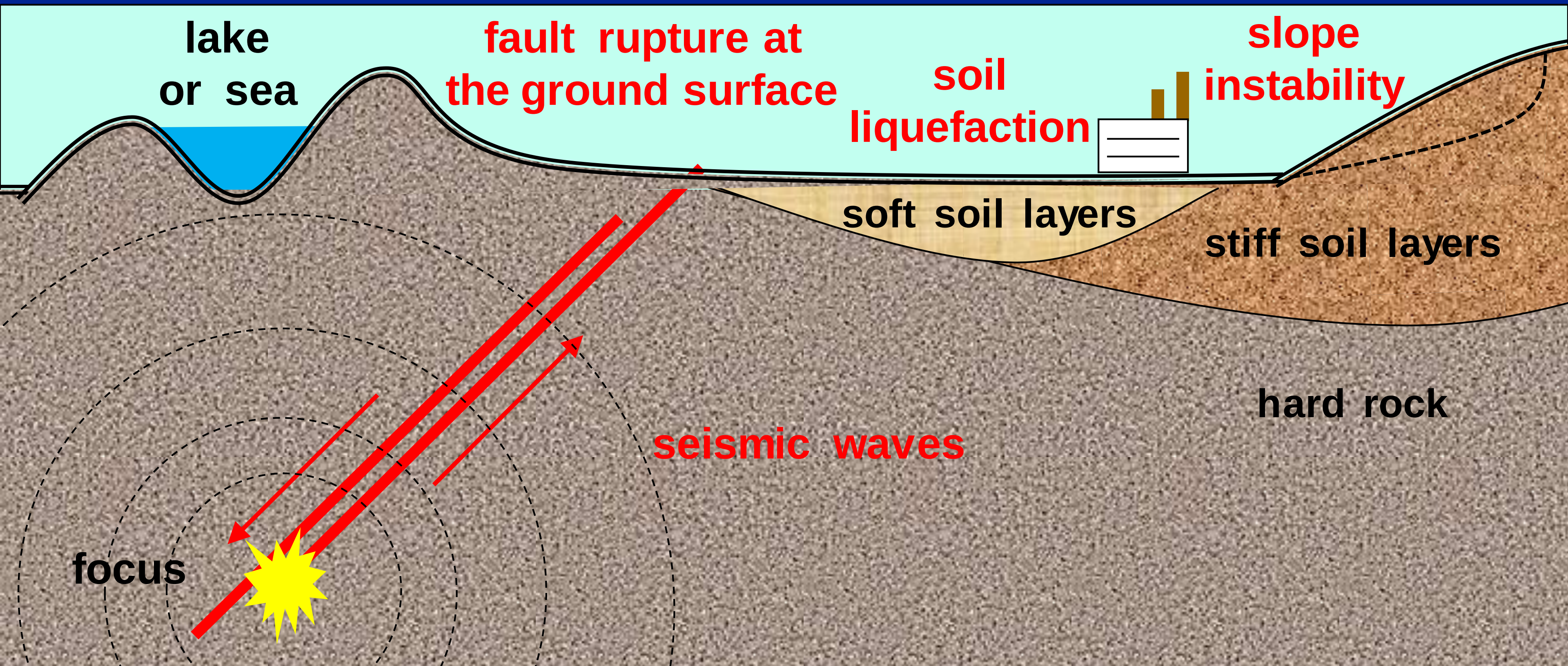
In areas characterized by seismicity
various earthquake-related geohazards exist



Note: This type of maps do not take into account local site conditions (i.e., soil, topography) and they refer only to onshore seismic hazard

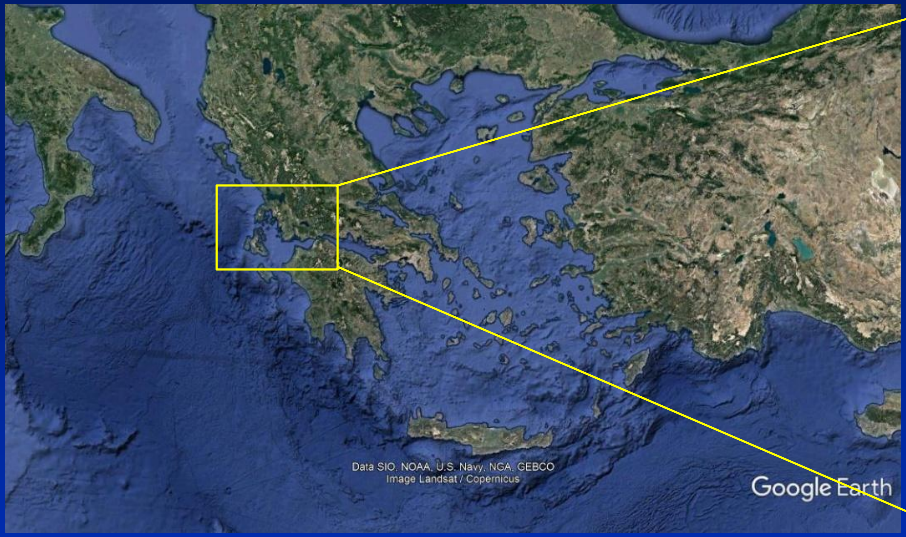
Earthquake-related geohazards

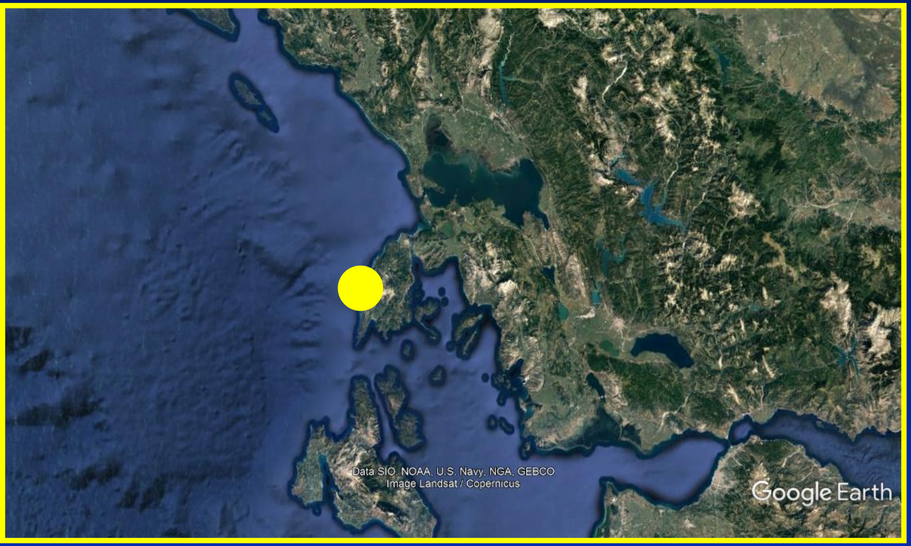
1. Strong ground motion (dynamic loading)
   due to seismic waves and local site conditions
2. Permanent ground displacements (quasi-static loading)
   due to fault rupture, soil liquefaction, and/or slope instabilities



Example of coastal landslides in west Greece

Lefkada earthquake, 2015 (M ≈ 6.5)





Vulnerability of industrial facilities and pipelines

Damages during earthquakes

damages to buried pipelines
during the
1971 San Fernando eq. in USA

damaged oil tanks
during the
1999 Kocaeli eq. in Turkey

Vulnerability of industrial facilities and pipelines

Failures during earthquakes

Natural gas storage tanks alight at the Cosmo oil refinery in Ichihara, Chiba Prefecture, in Japan in 2011

Türpas Izmit refinery plant during the 1999 Kocaeli eq. in Turkey

Soil – structure interaction (SSI) and seismic design

SSI may be categorized as:

a) dynamic
b) quasi – static

Seismic design may be categorized as :

a) seismic design of <u>“local” projects with mass</u> where induced acceleration is taken into account
b) seismic design of <u>“extensive” projects with limited mass</u> where induced PGDs are taken into account

Methodology for the seismic design of pipelines

1. Avoidance of the potentially problematic area(s) by pipeline re-routing (or tunnelling)

2. Application of various geotechnical mitigation measures aiming to avoid the occurrence of the potential earthquake-related geohazard(s)

3. Crossing through problematic area(s) with "isolation" techniques (after SSI analyses)

4. Crossing through the potentially problematic area(s) without any mitigation measure (after SSI analyses)

Note: In the case of offshore gas pipelines in deep waters

a) the design must be very conservative since a local failure may lead to a complete destruction of the whole pipeline.

b) the application of mitigation / isolation measures is rather impossible

Therefore, the first method (i.e. rerouting) is preferred.

Seismic design of energy projects

Under static conditions, the design of an energy project is a straightforward procedure since the uncertainties are rather limited

Under seismic conditions, the uncertainties are high. Therefore, we need a design that will be based on statistical interpretation of data and probabilistic analysis:

(Structural Risk) = (Hazard) x (Vulnerability)

and

(Total Risk) = (Structural Risk) x (Loss) $\Rightarrow$

(Total Risk) = [(Hazard) x (Vulnerability)] x (Loss)

Remote sensing and early-response systems

Usually, emphasis is given only on the seismic response of engineering projects during their design phase

Nevertheless, the application of remote sensing and early-response systems during the operation phase may substantially decrease the total risk, TR, by

a) Monitoring (and reducing - if possible) the loading (i.e. the Hazard, H)

b) Monitoring (and reducing - if possible) the structural response (i.e. the Vulnerability, V)

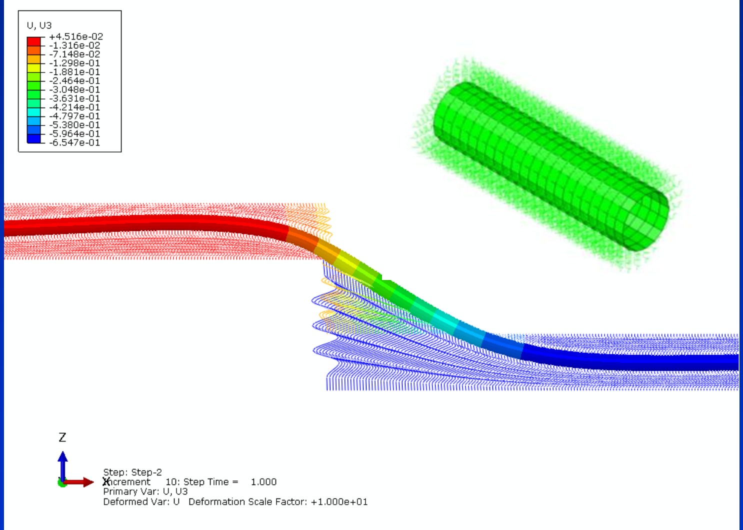
c) Monitoring (and reducing – if possible) the Loss, L

(Total Risk) = [(Hazard) x (Vulnerability)] x (Loss)

Remote sensing and early-response systems

Why sensing and early-response systems are required ?

1. Human errors and negligence during the design, construction and/or operation phase cannot be excluded.



Additionally, standards and norms are not perfect and they are getting improved every 10 – 20 years.

Remote sensing and early-response systems

Why sensing and early-response systems are required ?

2. All input data have a certain degree of uncertainty, and climate change makes this uncertainty even higher (e.g. heavy rainfalls increase the risk of landsliding under static and seismic conditions)

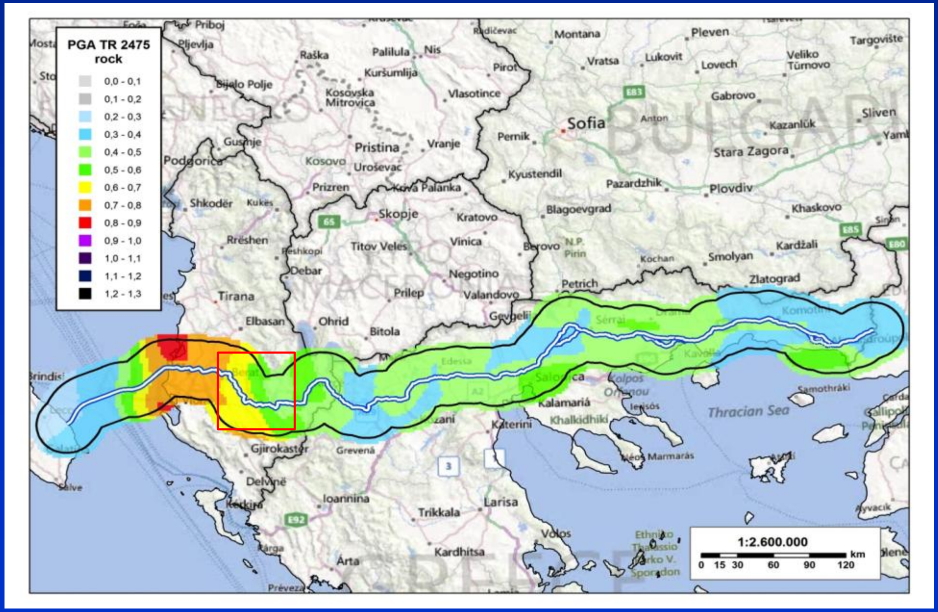
2001 El Salvador earthquake

1995 Kobe earthquake (Japan)

Remote sensing and early-response systems

Why sensing and early-response systems are required ?

3. Seismic design relies on seismological studies based on probabilities and statistical interpretation of data



Seismological map showing
the acceleration levels along TAP

Remote sensing and early-response systems

Why sensing and early-response systems are required ?

4. Some projects are located in remote isolated areas, with limited accessibility (e.g. mountains) or even zero accessibility (e.g. deep sea)

steep slopes in central Albania
(≈ + 2 km)

deep waters of the Mediterranean Sea
(≈ - 5 km)

Remote sensing and early-response systems

Why sensing and early-response systems are required ?

5. As modern seismic design allows certain damage levels, a relatively small aftershock may cause the collapse of a damaged structure if the structural damages of the mainshock have not been identified and repaired quickly

damaged oil tanks during
the 1999 Kocaeli earthquake in Turkey

Remote sensing and early-response systems

Why sensing and early-response systems are required ?

6. An early-response system (e.g. a smart block valve that connects components) may decrease the loss of new or old facilities, and therefore the total risk

oil tanks and pipelines
connected with a marine jetty in Cyprus

Remote sensing and early-response systems

In order to have a remote and complete real-time view of the potential phenomena, there is need for the installation of the following (in parallel)

1. accelerometers
2. inclinometers, topographical instrumentation, and/or satellites
3. strain gauges and/or fibre optics
4. meteorological (weather) stations

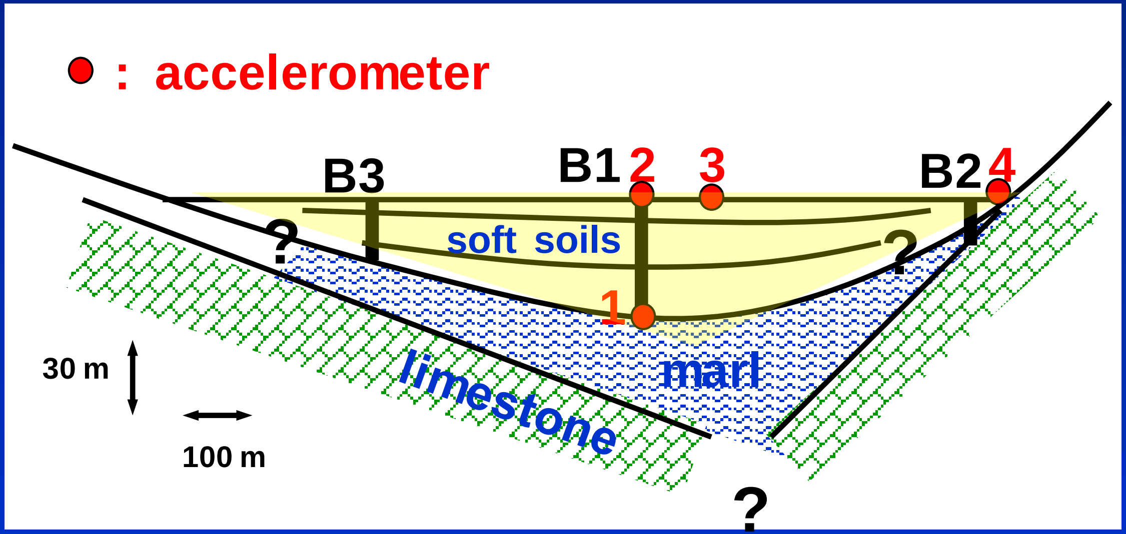
and the development of

a) early-warning systems, and/or
b) early-response systems (on the pipeline and the CSs)

Remote sensing and early-response systems

1. Accelerometers

for the recording of the triggering
(i.e. seismic motion at ground base and ground surface)



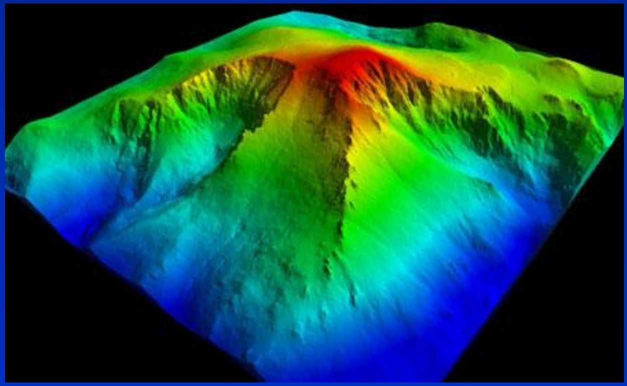
Acceleration measurements
at the Cephalonia seismic array
(after Psarropoulos et al. 1999)

Remote sensing and early-response systems

2. Inclinometers, topographical instrumentation, or satellites in order to measure permanent ground displacements (due to slope instabilities, soil liquefaction, fault rupture)

Example of subsurface measurement with inclinometer

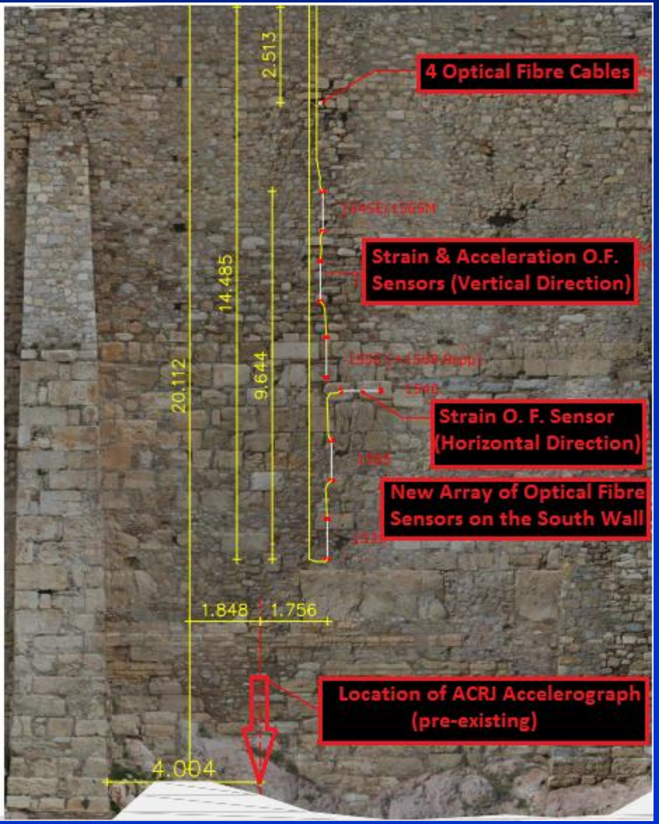
Example of surface measurement with geodetic instruments



Example of surface measurement with LiDaR

Remote sensing and early-response systems

3. Early-warning and early-response systems
connected with strain gauges, fibre optics, etc.
measuring the structural distress (e.g. strain levels)



Example of remote sensing
at the Hill and Circuit Wall
of the Acropolis of Athens
(after Psarropoulos et al. 2018)

Remote monitoring and early-response systems

4. Meteorological (weather) stations
monitoring wind speed, temperature, humidity, rain, etc.

Meteorological (weather) station in Greece

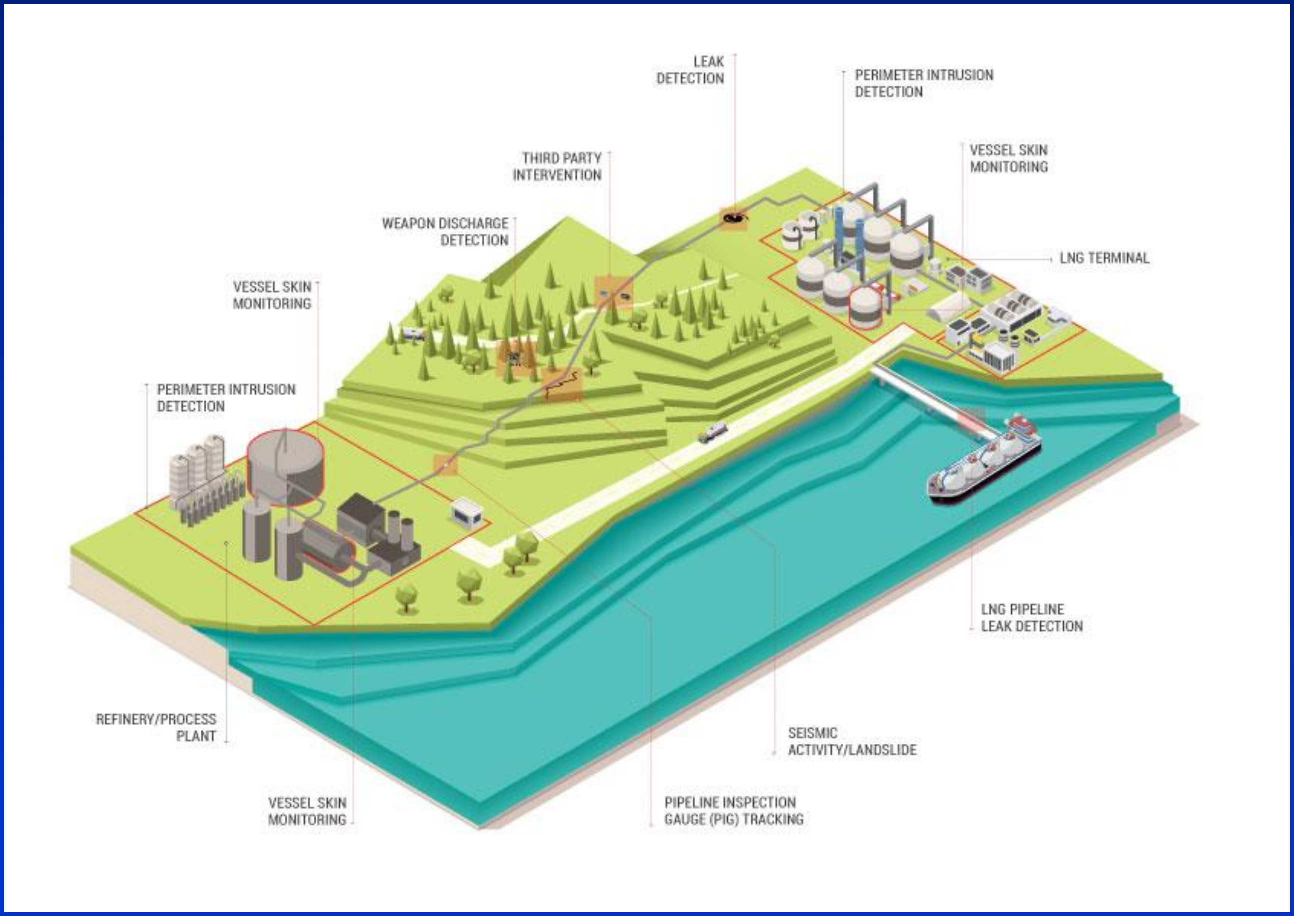
Need for remote monitoring depending on the circumstances and the local site conditions

	Onshore pipeline		Offshore pipeline	
	High accessibility (flat terrain)	Low accessibility (mountains)	High accessibility (shallow waters)	Low accessibility (deep waters)
Static conditions (low uncertainty)	Low need for monitoring	Medium need for monitoring	Medium need for monitoring	High need for monitoring
Seismic conditions (high uncertainty)	Medium need for monitoring	High need for monitoring	High need for monitoring	Very high need for monitoring

Note: Application of monitoring on offshore pipelines, especially at deep waters, may have various difficulties and high cost (at least for the time being)

Combined monitoring of critical infrastructures

in order to achieve safety, security (and cyber-security)



Combined monitoring of critical infrastructures

in order to achieve safety, security (and cyber-security)

An onshore or offshore critical infrastructure
may be very vulnerable to
a terrorist attack (physical and/or cyber)
just after a serious damage
that has been caused by a natural phenomenon
(e.g. earthquake, tsunami, storm, etc.)

General conclusions (1 / 3)

In the near future new major gas pipelines are expected to be designed and constructed in many areas (onshore, near-shore, and/or offshore)

Many of these areas are characterized by seismicity and earthquake-related geohazards, a fact that makes the design (and operation) of any engineering project a more demanding and challenging task, especially when risk minimization and cost-effectiveness are required in parallel.

General conclusions (2 / 3)

The simplistic provisions of national and international seismic norms are rather incapable to cover sufficiently all issues of geohazard assessment and seismic design of gas pipelines (especially offshore).

The optimum seismic design of a pipeline project requires, apart from geoscientists familiar with qualitative geohazard assessment, engineers capable to perform the following:

a) quantitative geohazard assessment (based on reliable data),
b) realistic soil-structure interaction analyses, and
c) optimum design of various geotechnical and/or structural mitigation measures (if required)

General conclusions (3 / 3)

Remote sensing, early warning and early-response systems have various benefits since they:

a) can substantially contribute to the reduction of the risk of various gas pipelines, either onshore or offshore.
b) may be very effective in the case of long gas pipelines that are crossing extensive and remote areas, characterized by potential geohazards and various meteorological conditions.
c) are very promising as new technologies (on sensors, telecommunications, and automations) are leading to a decrease of their cost and an increase of their reliability.

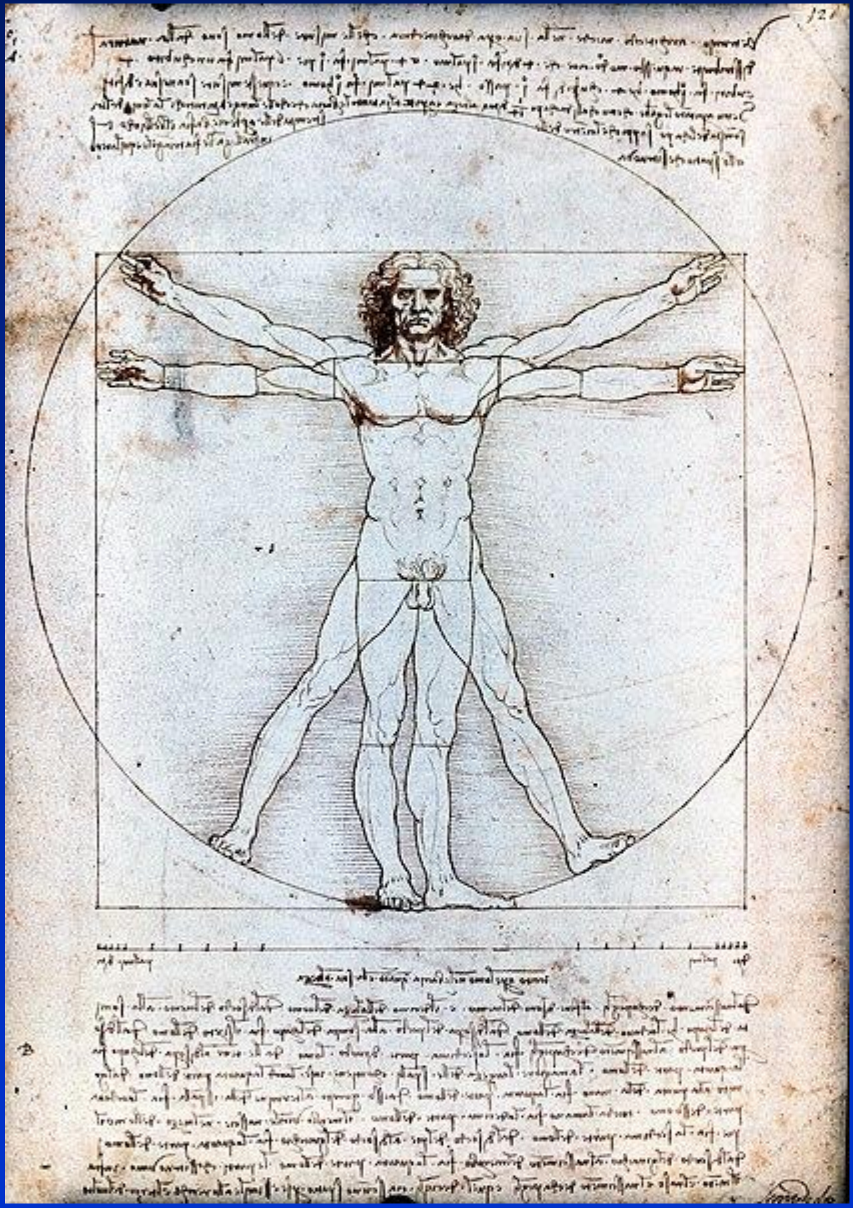
Epilogue: Structural engineering vs. biomechanics

Human body, being a
"very smart structure", has:

Sensors (eyes, ears, etc.)
to monitor the "hazard(s)" and
brain (i.e. neural networks) to

a) assess rapidly the "vulnerability" and
b) mobilize legs, hands and other instruments in order to respond (if required) by avoidance, isolation or mitigation measures and to reduce the "total risk"

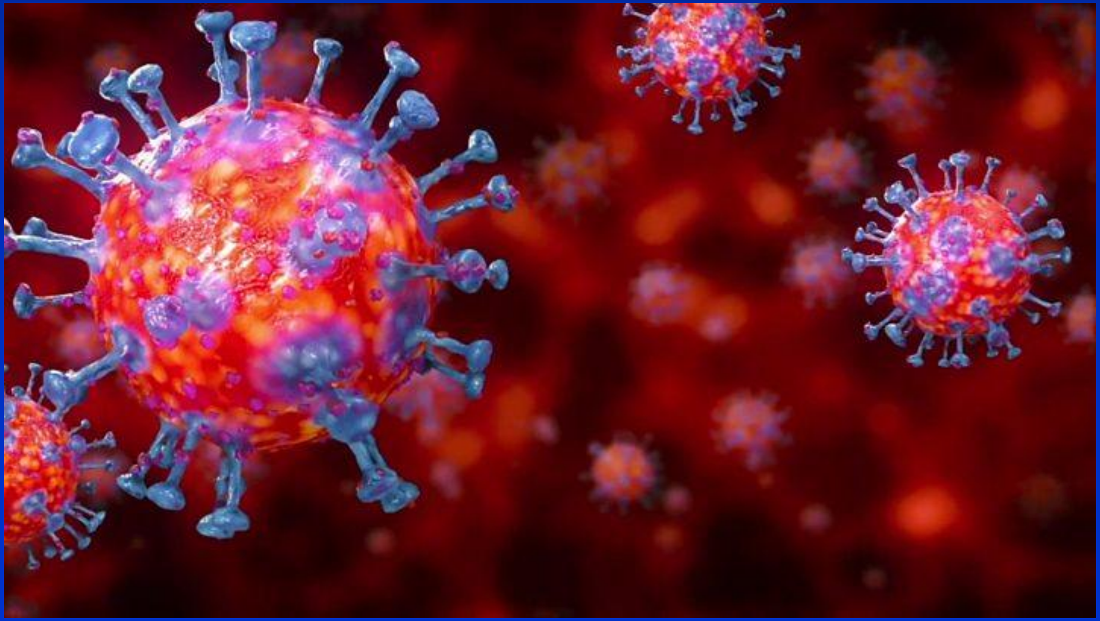
$$(TR) = [(H) \times (V)] \times (L)$$



Epilogue: Structural engineering vs. biomechanics

If the hazard cannot be quantified due to the incapability of our sensors to monitor it or lack of previous data (see coronavirus), then we cannot estimate vulnerability and total loss…

Nevertheless, avoidance of hazard (see lockdown) may be a very inconvenient and expensive option…



Thank you very much for your attention !

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