UNIVERSITA’ DEGLI STUDI DI PALERMO

Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali

The Italian contribution to the analysis of the effects of earthquakes on water supply systems: practical experiences and theoretical investigations

Mario Rosario Mazzola, Maurizio Giugni, Roberto Guercio and Antonio De Risi

Sixth Taiwan-US-Japan

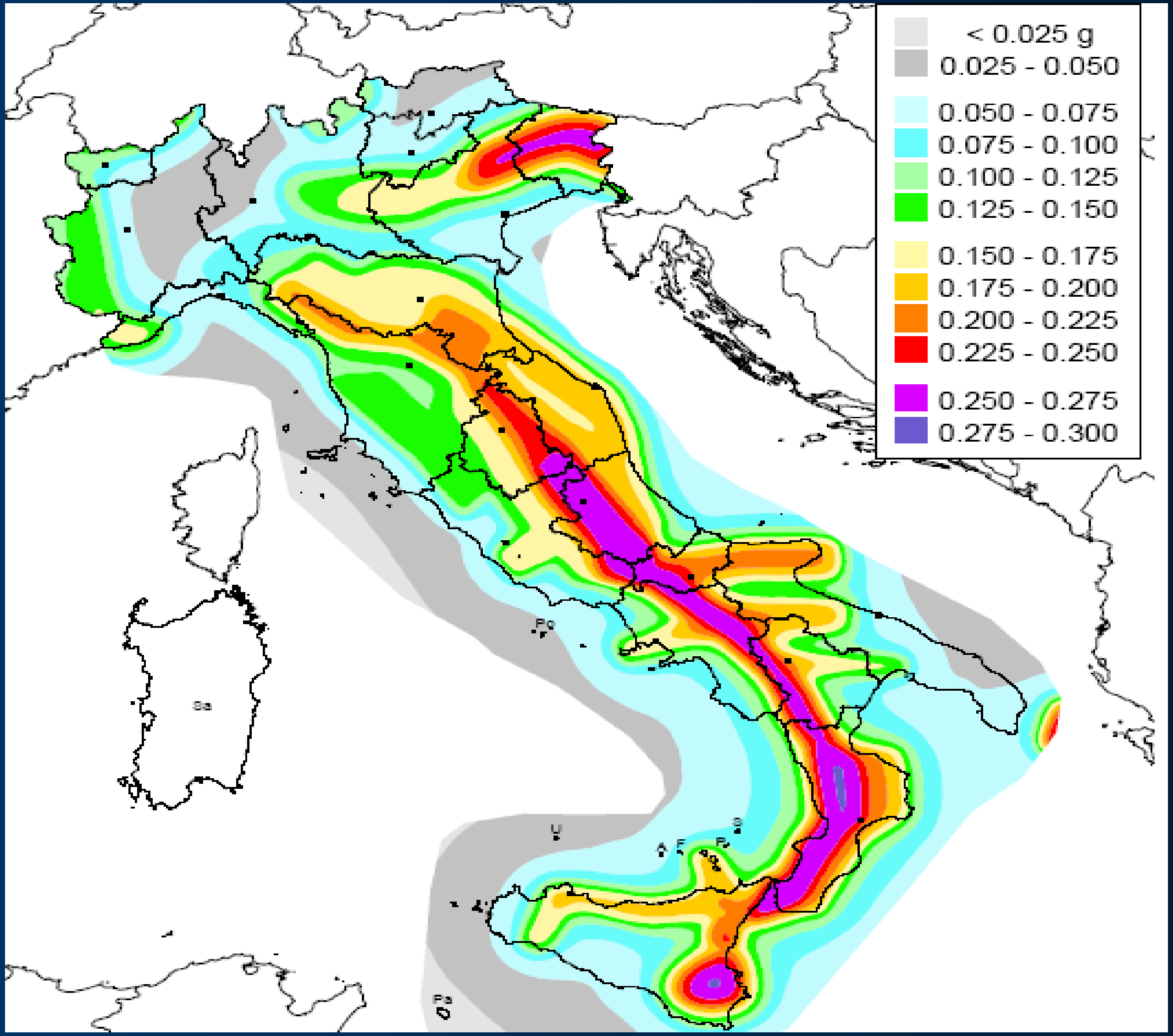
Workshop on Water System Seismic Practices

Presentation outline

- Seismic features of Italy
- The effect of earthquakes on groundwater resources after some disastrous events on the Appennines
- Theoretical contributions: a finite length beam model of pipe displacement due to earthquakes

Seismic features of Italy

◆ **Seismic hazard as 10% exceedance probability maximum ground acceleration in 50 years**



Disastrous earthquakes in Italy in the XX and XXI century

- **Messina in Sicily (1908) magnitude 7.2 with over 82,000 victims;**
- **Avezzano in Abruzzi (1915), magnitude 7.0 where around 32,000 were killed;**
- **Irpinia (1930) in Campania, magnitude 6.5 with around 1,400 victims;**
- **Belice (1968) in Sicily, magnitude 6.4 with 370 victims and 70,000 homeless;**
- **Friuli (1976), with 976 killed and 70,000 homeless;**
- **Irpinia (1980) magnitude 6.9 with 2,735 killed and over 7,500 injured;**
- **Abruzzo (2009) where 300 persons were killed by a 5.8 magnitude earthquake.**

Impact of eartquakes on supply sources – Ruzzo springs after the Abbruzzo eartquake (2009) - 1

- **The Appennines feature large aquifers on stratified carbonatic rocks with few highly fractured areas;**

- **The hydraulic transmissivity of the aquifer is basically related to the degree of fracturation;**

- **Ruzzo springs used to constitute the main supply source for the Teramo province in Abruzzo until the construction of the Gran Sasso tunnel and the laboratories of the National Institute of Nuclear Physics (INFN) in the ‘80s;**

- **These large infrastructures have altered significantly the flow regime of the springs, causing an overall, consisting reduction of yield.**

Impact of eartquakes on supply sources – Ruzzo springs after the Abbruzzo eartquake (2009) – 2. Hydrogeology of Gran Sasso

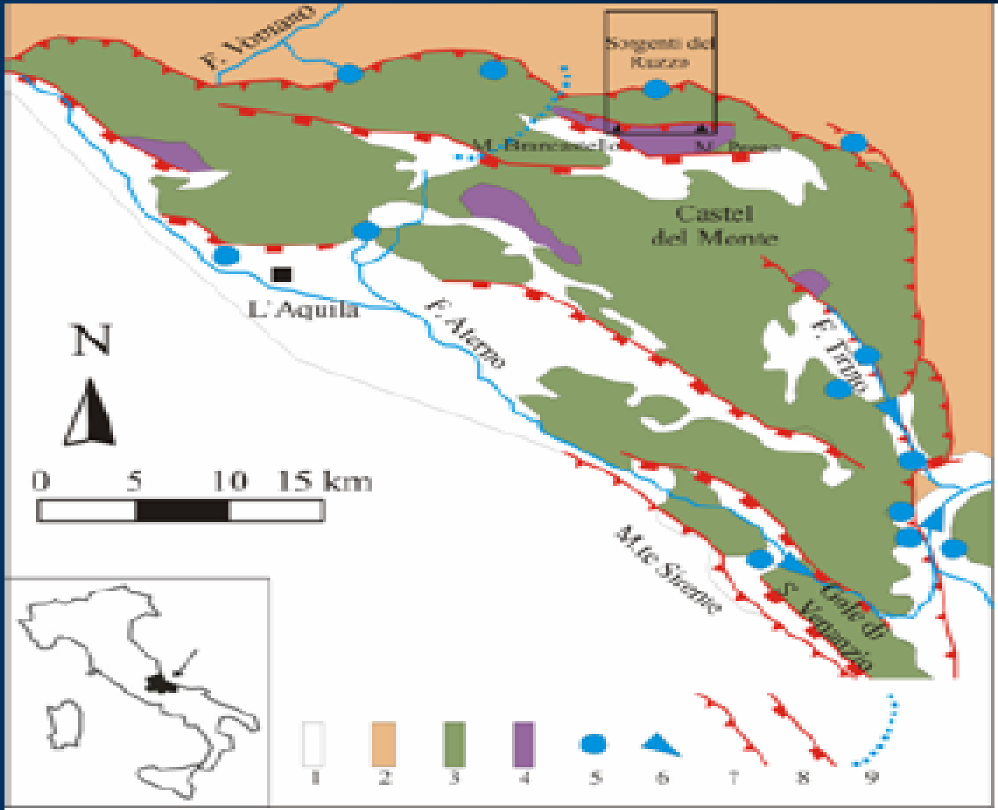


Figure 1. Hydrogeologic system of Gran Sasso d'Italia (Abruzzi, Italy). 1, aquitard, clastic continental deposits of intermontane troughs (Quaternary); 2, aquiclude, foredeep torbidite terrigenous deposits (Miocene-Pliocene); 3, aquifer, carbonate platform and deep ramp successions (Mesozoic-Cenozoic); 4, low permeability dolomite substratum (upper Triassic); 5, most important spring; 6, linear spring; 7, thrust; 8, normal fault; 9, drainage by highway tunnel (from Petitta & Tallini, 2002 modified).

Impact of eartquakes on supply sources – Ruzzo springs after the Abbruzzo eartquake (2009) – 3. Hydrogeology of Ruzzo Springs

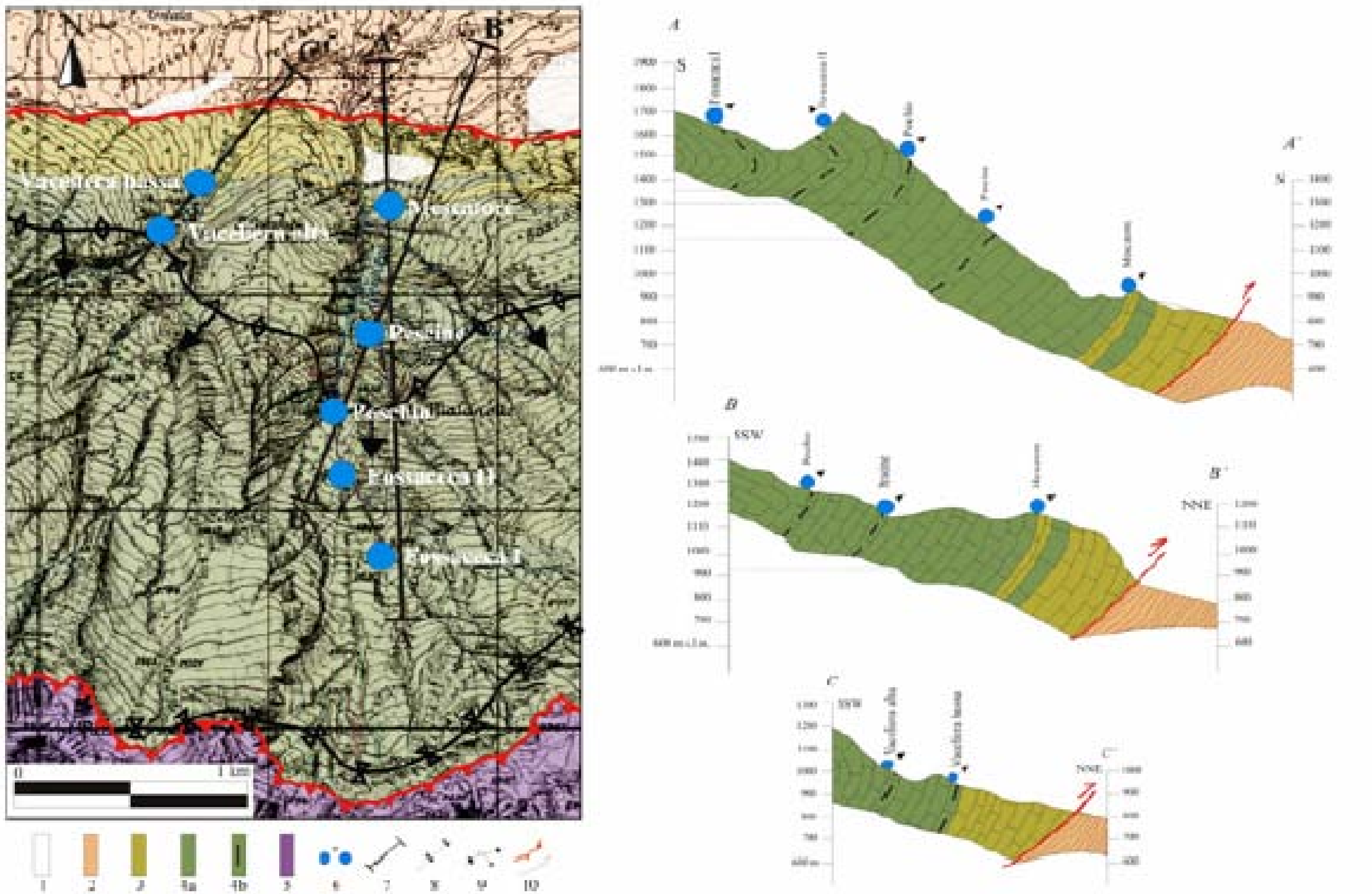


Figure 2. Hydrogeologic map and cross-sections of Ruzzo springs zone. 1, hydrogeologic complex of recent detrital continental units; 2, marine terrigenous units complex; 3, marly complex; 4a, calcareous complex; 4b, marly and/or competent levels inside calcareous complex; 5, dolomite complex; 6, spring; 7, cross-section; 8, syncline axis; 9, overturned anticline axis; 10, thrust.

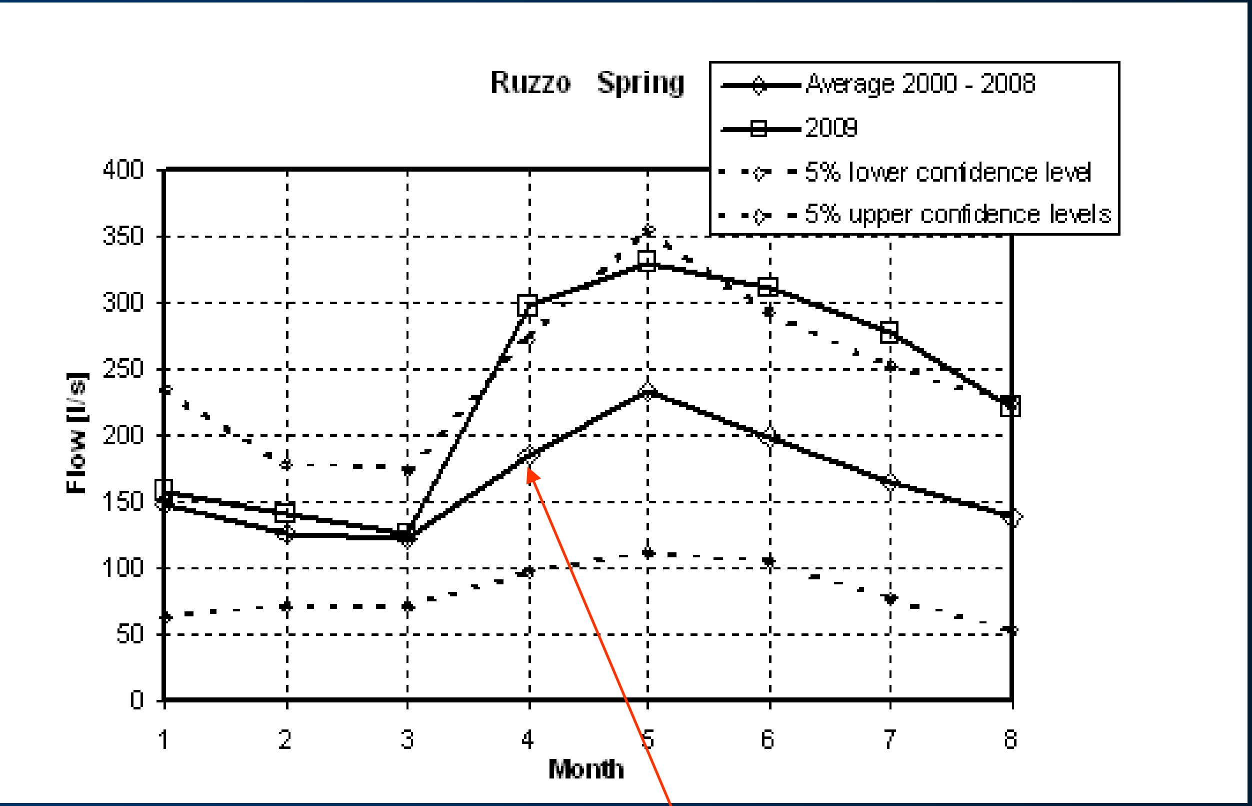
Impact of eartquakes on supply sources – Ruzzo springs after the Abbruzzo eartquake (2009) – 4. Hydrogeology of Ruzzo Springs

- **Ruzzo springs have short circuit connected to basal groundwater because, in their zone, fractured calcareous litologies outcrop alternate with either other less/not fractured litologies or with marly litologies;**

- **The connection takes places on the tectonic contact between the cretacean-eocenic carbonatic complex and the miocenic marlic bed;**

- **The activation of such tectonic contact during the recent (April 2009) earthquake in Abruzzo may be responsible for the overall increase of discharge recorded shortly after the earthquake.**

Impact of eartquakes on supply sources – Ruzzo springs after the Abbruzzo eartquake (2009) – 5. Flow pattern of Ruzzo Springs

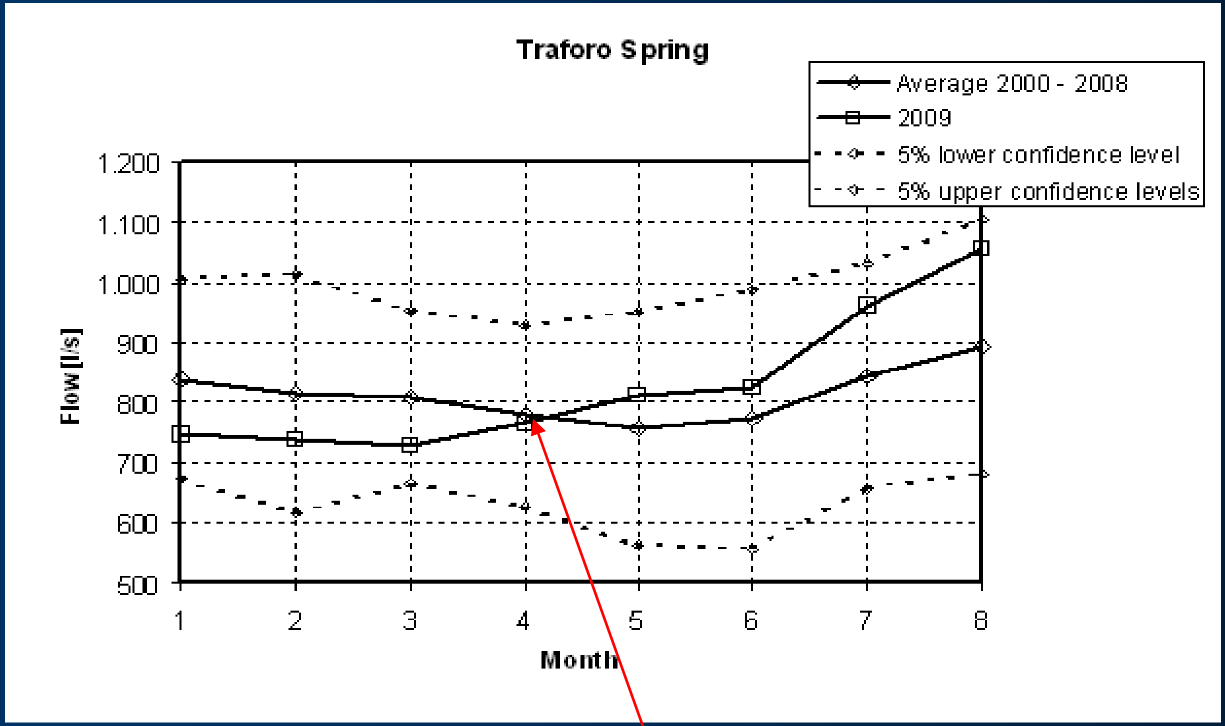


Earthquake 06.04.09

5% confidence intervals for average monthly values obtained by assuming that monthly yields are normally distributed with standard deviation as estimated by 2000-2008 data

Impact of eartquakes on supply sources – Ruzzo springs after the Abbruzzo eartquake (2009) – 5. Flow pattern of Ruzzo Springs

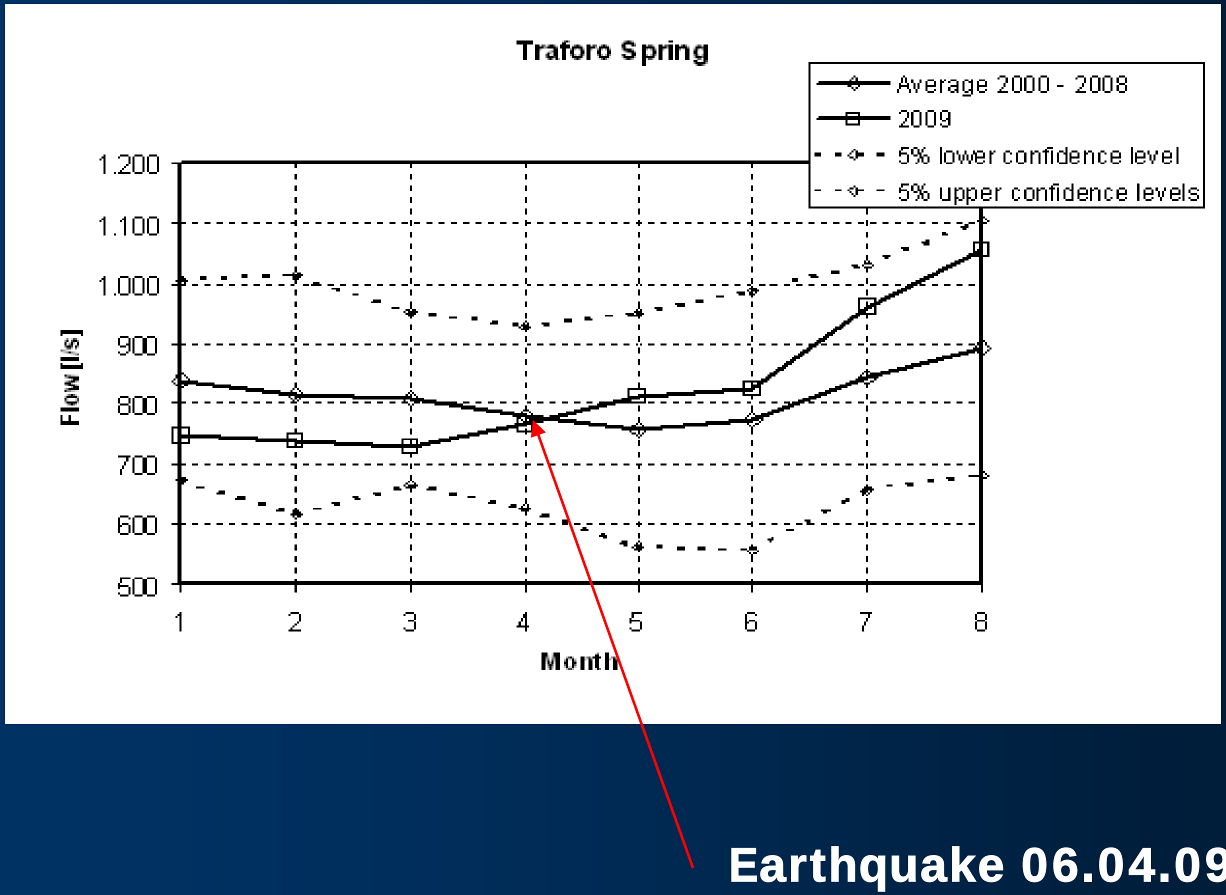
… a similar, albeit softer, pattern has been recorded for other important springs in the area



Earthquake 06.04.09

Impact of eartquakes on supply sources – Ruzzo springs after the Abbruzzo eartquake (2009) – 5. Flow pattern of Ruzzo Springs

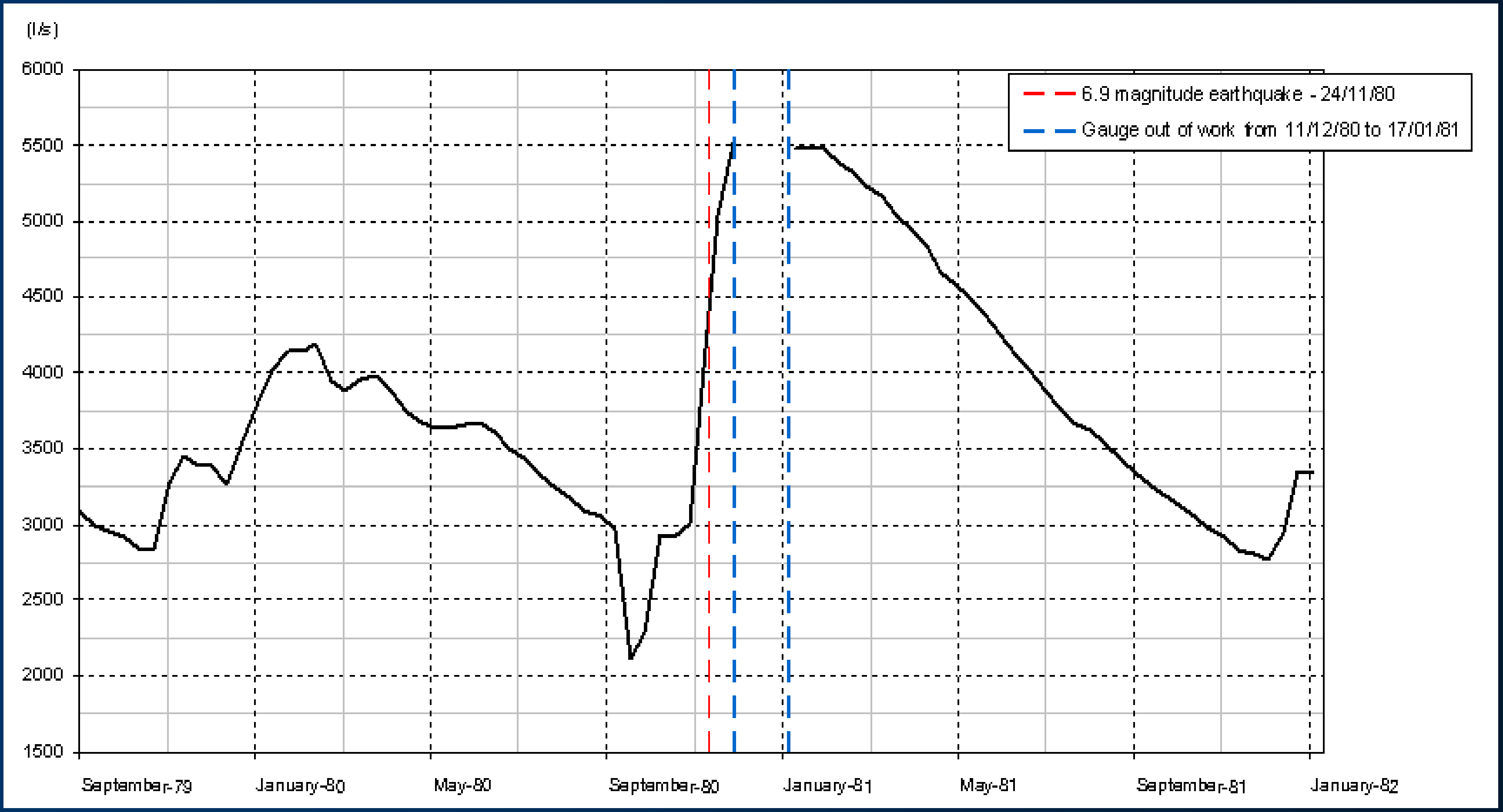
… a similar, albeit softer, pattern has been recorded for other important springs in the area



Impact of eartquakes on supply sources – Caposele and Cassano springs after the Irpinia eartquake (1980) /1

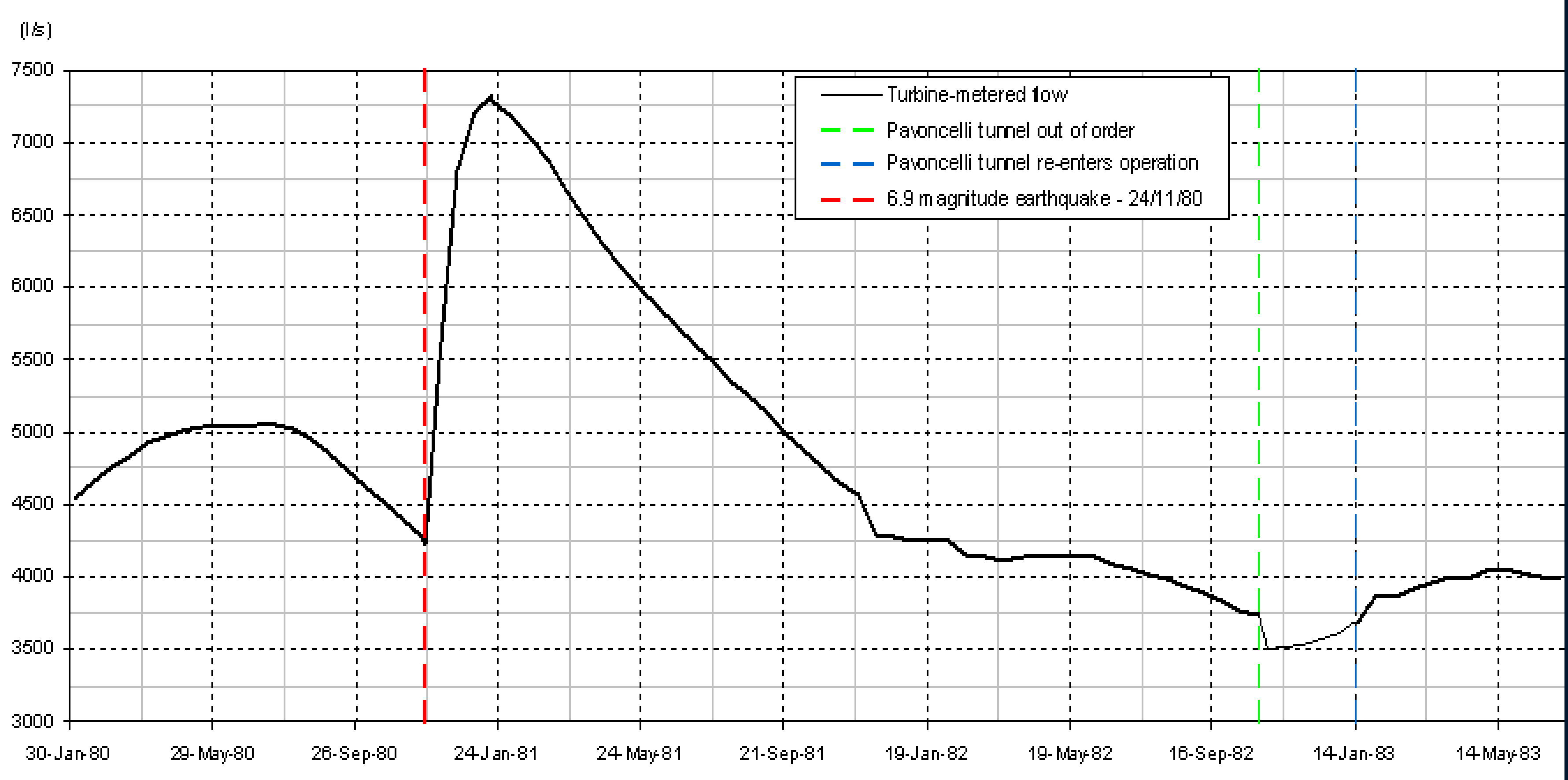
- Caposele and Cassano springs (around 6,0 m^3/s) flow both into the Pavoncelli Tunnel (12 km) and constitute the main source for the Acquedotto Pugliese (Apulian Aqueduct), now supplying around 4,000,000 persons;
- The aqueduct, with 55 km of tunnels, was built in the first three decades of the twentieth century;
- Ever since its construction, the tunnel had suffered from a number of damages that had been repaired in years 1926-29 and in year 1924; in those years, repairing of some cross-section resulted in the substitution of calcareous stone with bricks both in the pillars and in the tunnel cap;
- The earthquake further worsened the situation: due to partial collapses of some cross-sections in the tunnel, a constant decrease in the water flow, in the order of 10 l/s per week.
- The risk clearly was the total interruption of water supply to Apulia, should the collapses have entirely occluded some part of the tunnel

Impact of eartquakes on supply sources – Caposele and Cassano springs after the Irpinia eartquake (1980)/2



Cassano springs

Impact of eartquakes on supply sources – Caposele and Cassano springs after the Irpinia eartquake (1980)/3



Caposele springs

Impact of eartquakes on supply sources – Caposele and Cassano springs after the Irpinia eartquake (1980)/4 – getting out of emergency

- **It was decided to build a 21 km pressurized bypass (with nominal diameter of 850 to 1050 mm) for an emergency flow of 2 m^3/s, including a pumping station for a head of 310 m;**

- **It was completed in four months and entered operations in september 1982;**

- **After securing water supply to Apulia, care was taken of the tunnel;**

- **Three different standard cross-sections were devised, depending on the level of damage: cast iron centres for different parts of the section were inserted with jets of fiber reinforced concrete.**

Impact of eartquakes on supply sources – /5 – conclusions

- Earthquakes should be aknowledged as one of the sources of risk in water supply and an appropriated risk-based approach design of supply systems shoud be introduced

- Risk is related not only to the structural failure of tunnels or large buried assets, but also to significant variations of the supply schemes due to changes in aquifer configuration.

Theoretical contributions: a finite length beam model of pipe displacement due to earthquakes - introduction

- Investigating the dynamic behaviour of buried lifelines is a rather complex problem since it includes three dimensional dynamic analysis of the soil–structure system subject to seismic excitation;
- Ground – pipe interactions depend significantly on the characteristics of both soil (depth of the layer, density, shear modulus), and pipes (elastic modulus, diameter, thickness, pipe depth) and on ground acceleration;
- As a result, different types of modelling of the system are developed using different degrees of simplifications with the aim of evaluating seismic stresses in the pipelines;
- Early works made use of a rigid model where pipe strains are the same as the ground and pipe characteristics are ignored. Such approach has also been reproposed in a (relatively) recent draft for European legislation and allows an immediate assessment of the peak axial strain and of the curvature of the pipe.

Theoretical contributions: a finite length beam model of pipe displacement due to earthquakes – BDWF model

- Pipe is schematized as a beam on dynamic elastic foundation and soil as a bed of springs according to Winkler → the stress induced by the soil is directly proportional to the relative movement between the pipe and the soil (BDWF – Beam on Dynamic Winkler Foundation);
- This relationship is held to be valid both for transverse and axial displacement and assumes Winkler constant values according to nature and mechanical characteristics of the surrounding soil;
- Under these assumptions, the equations governing axial motion of the pipe subject to soil displacement Ug is:

$$-EA\frac{\partial^2 U}{\partial X^2} + m\frac{\partial^2 U}{\partial T^2} + K(U - U_g) = 0$$

- U: the pipe displacement in X direction (longitudinal direction), assumed the same as wave propagation,
- M: mass per unit length,
- E: Young's modulus of the pipe material,
- A=πs(DE-s) area of the cross section, where s and DE are the thickness and the external diameter of the pipe respectively, and K=kπDE, in which k is soil's Winkler constant.

Theoretical contributions: a finite length beam model of pipe displacement due to earthquakes – finite vs. infinite length models

- The infinite length model fail to account for the pipe's effective length and any construction works, such as anchoring blocks, branches, manholes and so forth, which inevitably modify the pipe behavior;
- These differences can be immediately inferred if we consider a water distribution or drainage network where branches, shafts or chambers can be expected at much smaller intervals;
- they also apply to external water supply pipelines where construction works can be envisaged, at most, every few hundred metres;
- a new approach was suggsted which schematizes the dynamic behavior of a finite length pipeline with different boundary conditions at its ends (FLBDWF – Finite Length Beam on Dynamic Winkler Foundation).

Theoretical contributions: a finite length beam model of pipe displacement due to earthquakes – assumptions and test cases for the FLBDWF

- **The pipeline is assumed to be continuous, i.e. any variations between the characteristics of the pipe and those of the joints are held to be negligible;**

- **a linear elastic soil model was assumed and no slippage at the pipe-soil interface was considered.**

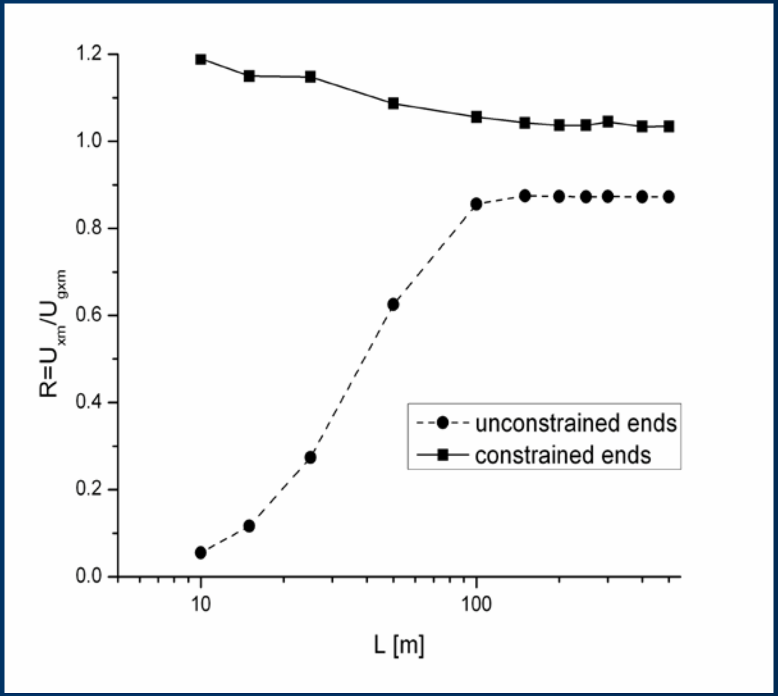
- **Since the end constrains of the pipe influence the seismic response, two different boundary conditions were considered: free ends and soil-constrained ends. The first assumption is sufficiently close to the pipe behavior when the constraints are such as to allow unrestrained deformation. The second boundary condition consists assumes that the constraints at either end of the pipe are such as to prevent all relative movement between the construction works and the pipe.**

- **Obviously the proposed boundary conditions are to be considered like borderline cases, only partially corresponding to the effective physical behavior of the oil-pipe system.**

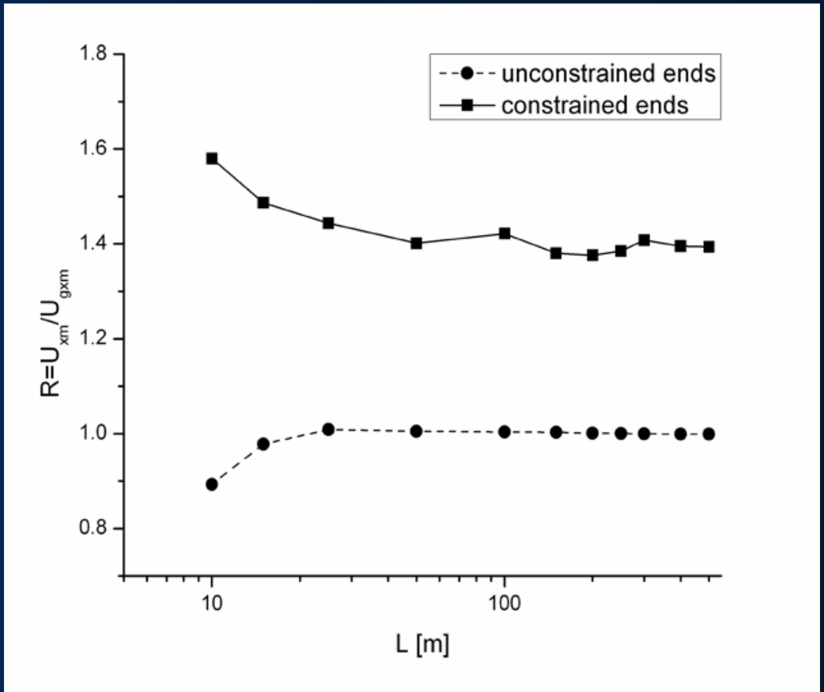
- **Numerical simulations: 1) steel and 2) HDPE pipes with a) free ends and b) soil-constrained ends . The effects of soil, pipe length and stiffness pipe on the seismic behavior were analysed emphasizing that the constraining condition at the pipe ends strongly affects its dynamic response.**

Theoretical contributions: a finite length beam model of pipe displacement due to earthquakes – Results 1

- Axial strain only
- Vs – propagation velocity through the soil: 200 m/s



Steel, D = 500 mm



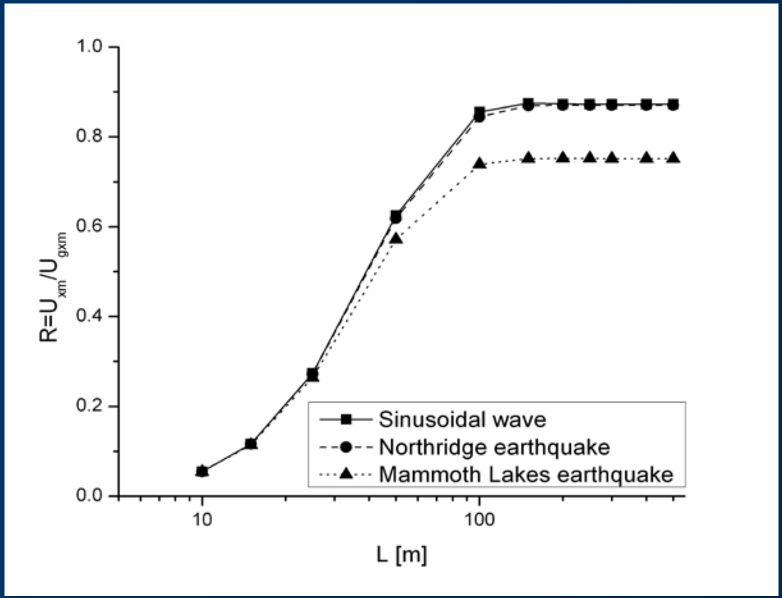
HDPE, D = 500 mm

Theoretical contributions: a finite length beam model of pipe displacement due to earthquakes – Results 2

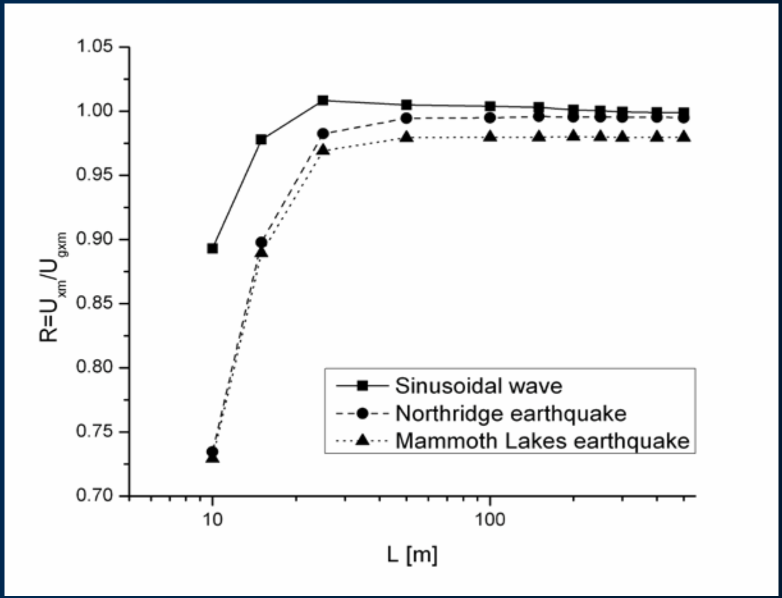
Actual soil motion (Northridge and Mammoth Lakes earthquakes)

Sinusoidal propagation wave

Unconstrained ends.....



Steel



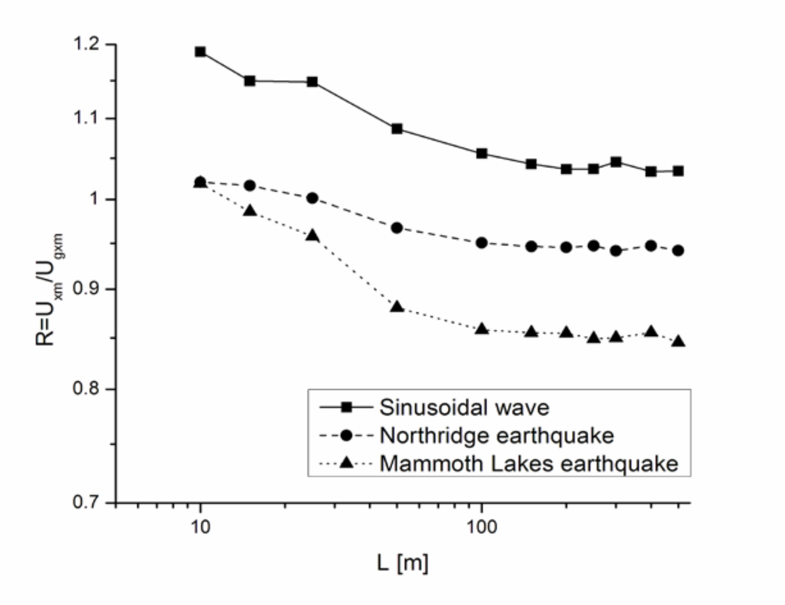
HDPE

Theoretical contributions: a finite length beam model of pipe displacement due to earthquakes – Results 3

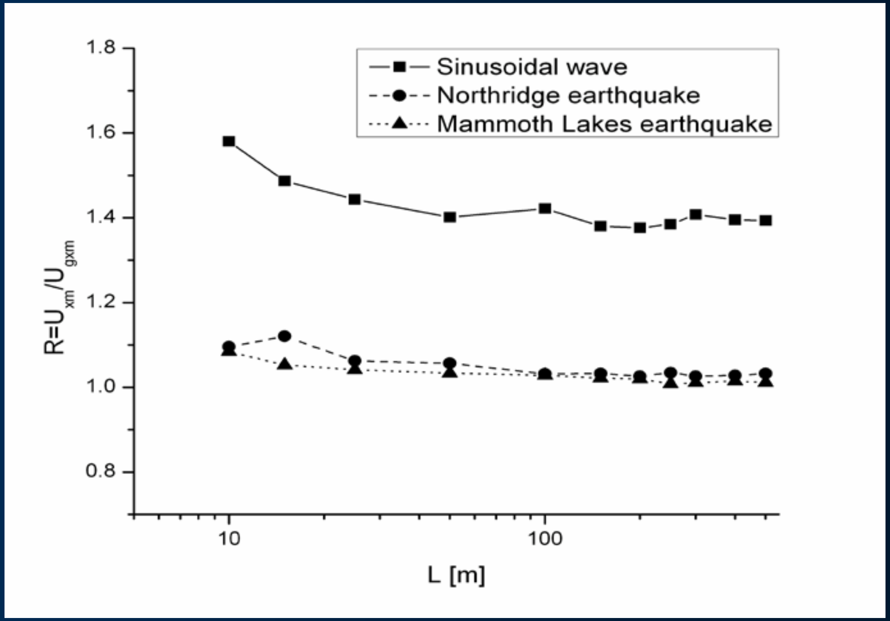
Actual soil motion (Northridge and Mammoth Lakes earthquakes)

Sinusoidal propagation wave

<u>Constrained ends</u>.....



Steel



HDPE

Conclusions

- Numerical simulations, now limited to axial strain, emphasized:

- for **free ends** pipes a BDWF (or rigid) model can be applied. Both the
- maximum axial displacement and the maximum axial strain of the pipe are similar to the soil one;

- for **constrained ends** pipes the Newmark model under-estimates the
- axial strain. According to the proposed approach, the maximum pipe strain strongly exceeds the soil one, particularly for HDPE pipes, for
- which short lengths attain greatest strains and hence the FLBDWF
- model could better estimate the pipe seismic stress.