

22 GENNAIO 2021

ITCOLD - COMITATO ITALIANO GRANDI DIGHE

Comportamento statico e sismico di dighe in terra zonate

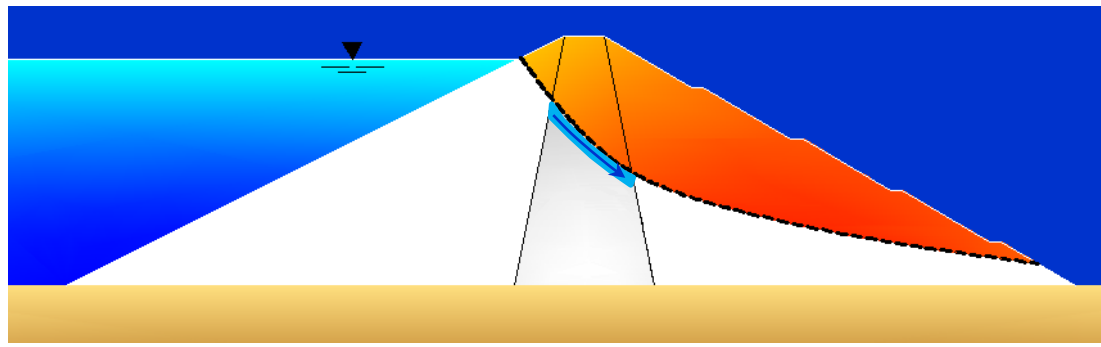
# Comportamento di dighe in terra sotto azioni sismiche

Luca Pagano  
Università di Napoli Federico II

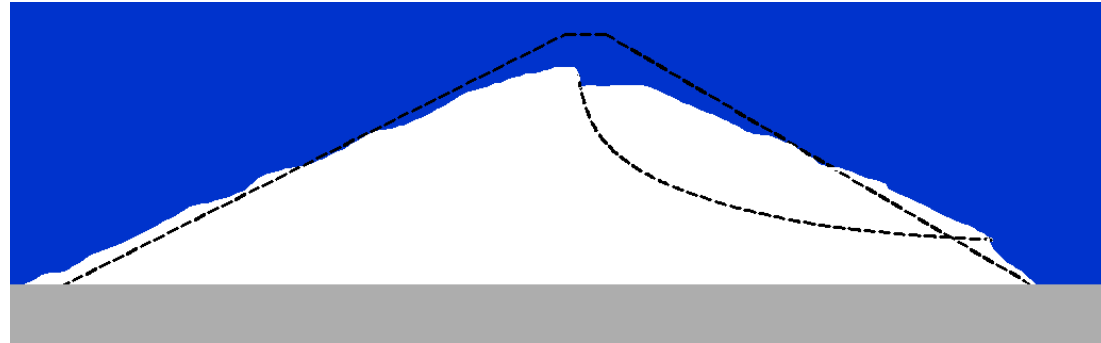
Stefania Sica  
Università del Sannio



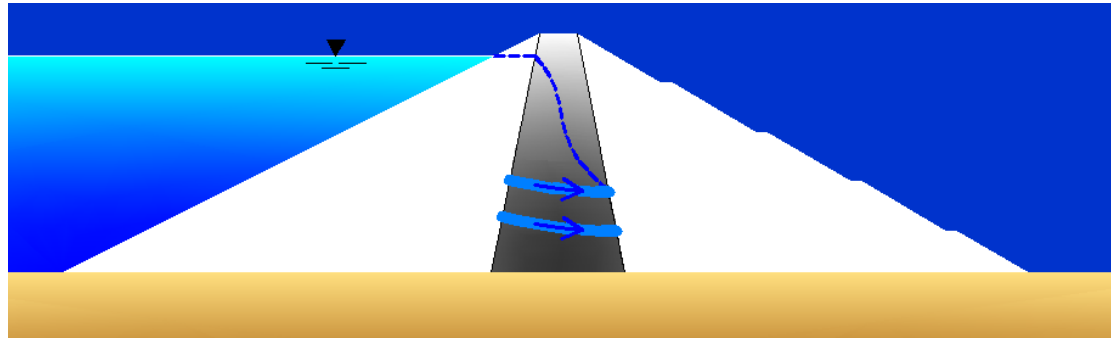
❑ INSTABILITA' GLOBALE



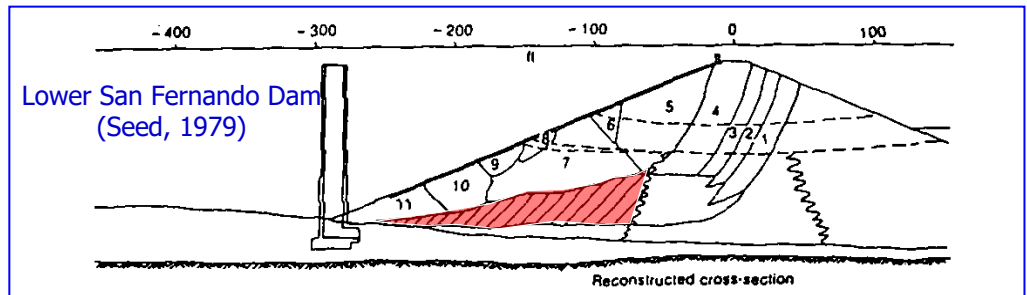
❑ RIDUZIONE DEL FRANCO



❑ FRATTURE ED EROSIONE



❑ LIQUEFAZIONE



- Caratterizzazione delle proprietà dei materiali da costruzione attraverso l'esame della documentazione esistente
- Osservazioni durante le fasi di esercizio
- Prove integrative
- Monitoraggio integrativo
- Analisi del comportamento sismico

# La diga del Camastra



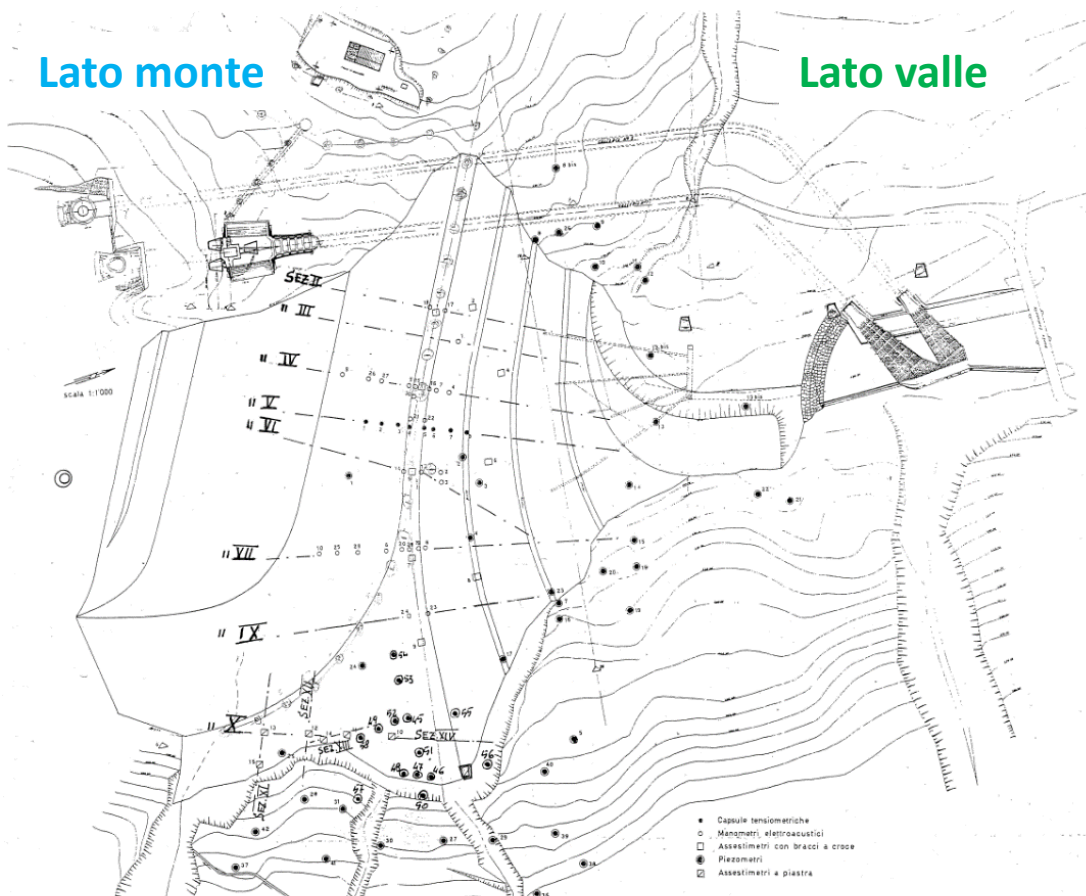




# La diga del Camastra

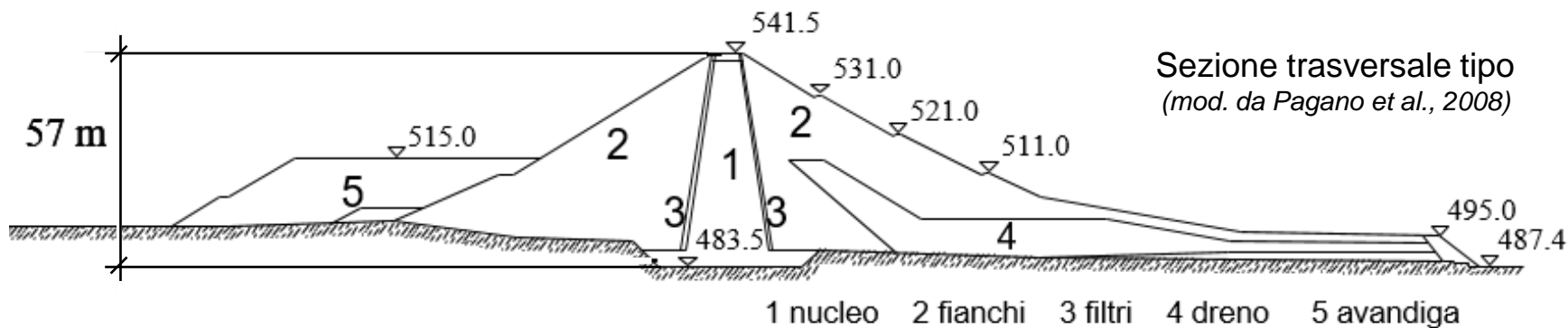
Lato monte

Lato valle



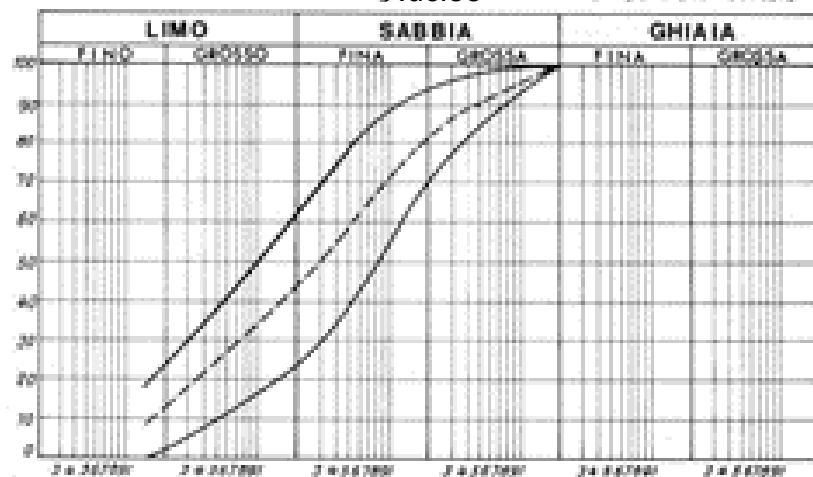
## DATI PRINCIPALI

Altezza della diga (ai sensi della L. 584/94)	57.00 m
Quota coronamento	541.50 m s.l.m.
Franco (ai sensi del D.M. 24.03.82)	6.90 m
Sviluppo del coronamento	371 m
Massima capacità dell'invaso	32·10 <sup>6</sup> m <sup>3</sup>

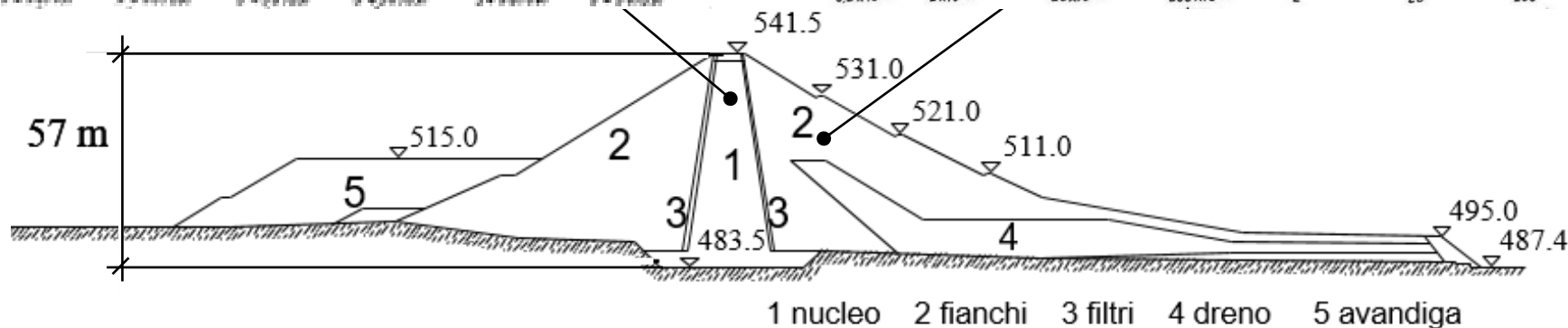
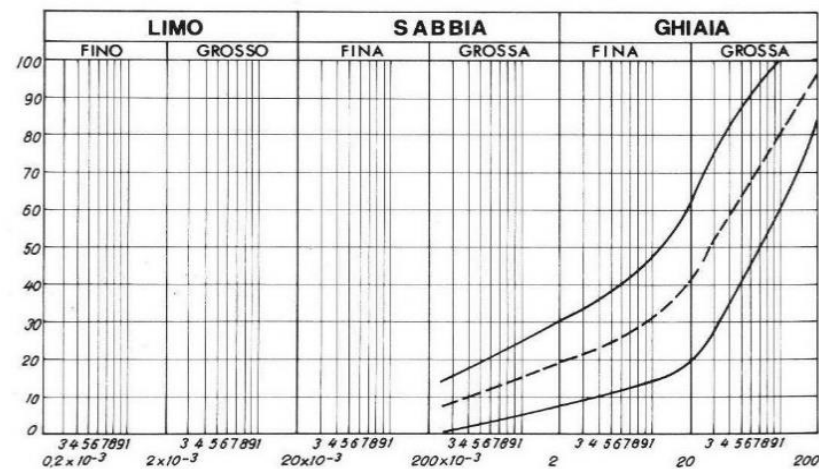


# Proprietà fisiche dei materiali

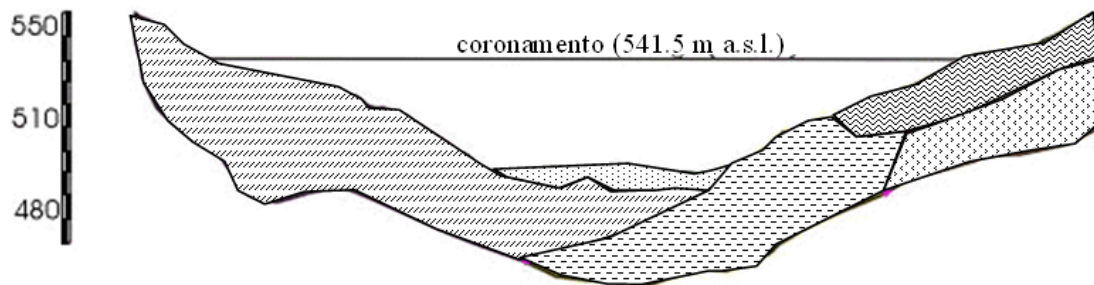
Nucleo








Fianchi

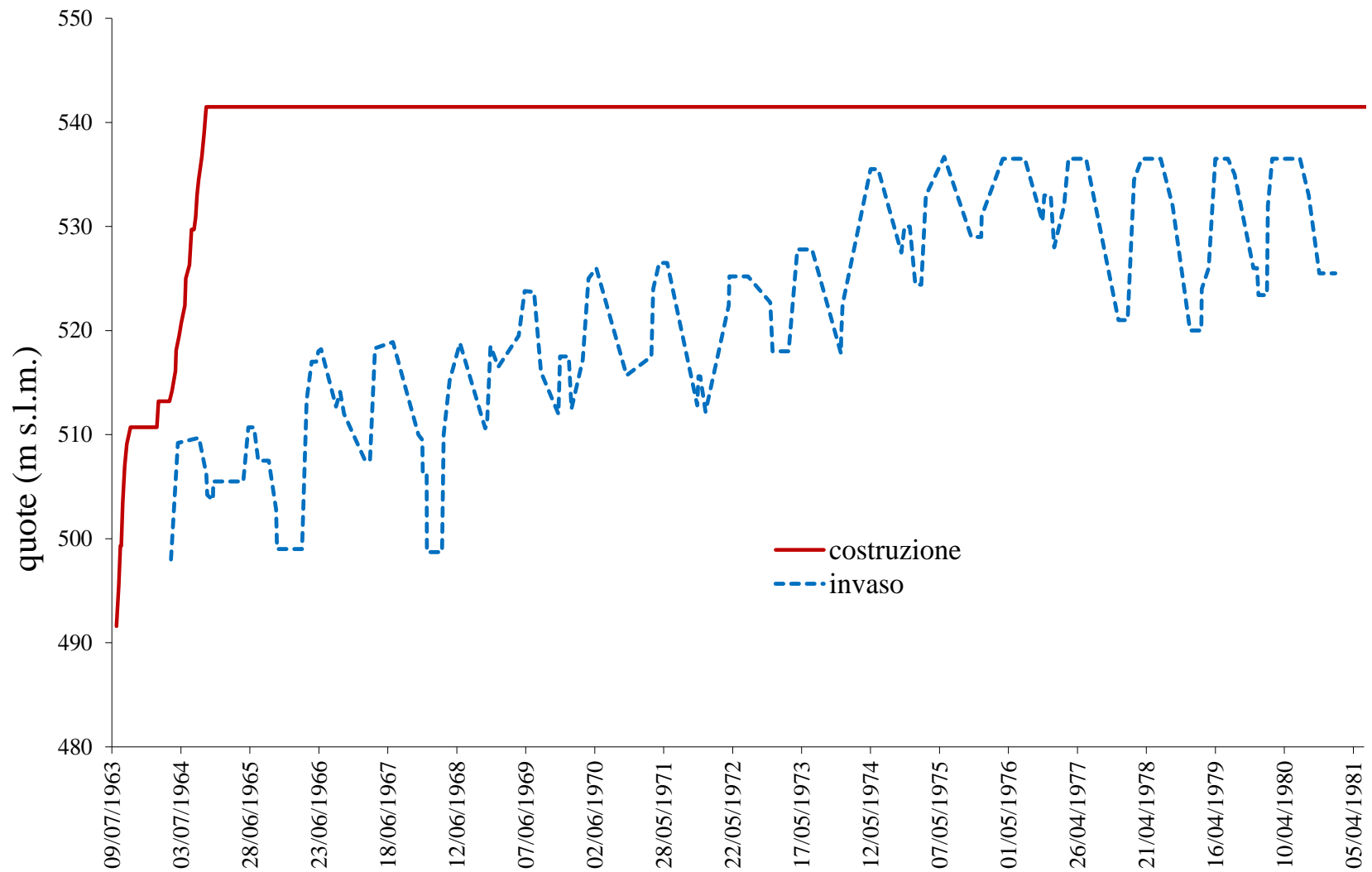


Sezione longitudinale



-  Alluvioni
-  Flysch di Gorgoglione (arenarie e argilliti)
-  Flysch di Serra Palazzo (argilliti e calcareniti)
-  Flysch di Corleto Perticara (argilliti e arenarie)
-  Detriti Arenaceo-argillosi

# Fasi di costruzione ed invaso



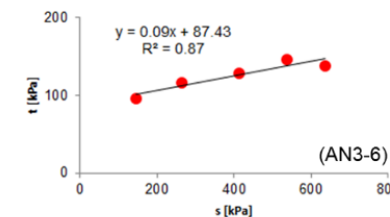
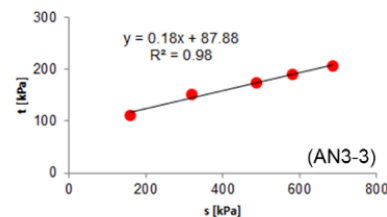
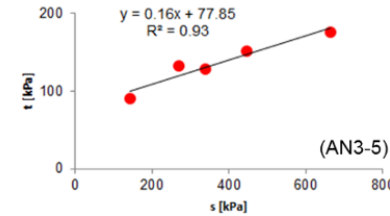
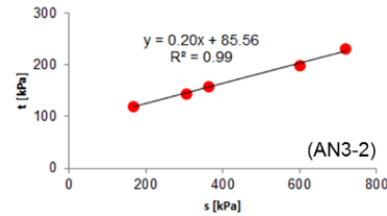
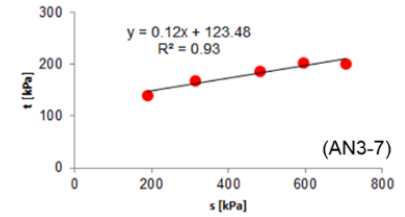
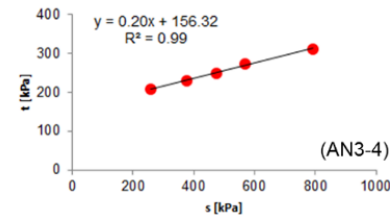
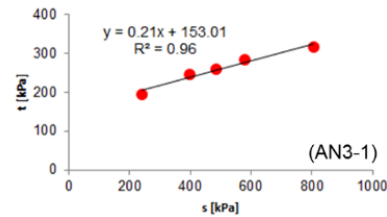


**DOCUMENTAZIONE DISPONIBILE DALLE FASI DI PROGETTO E  
CONTROLLO IN FASE COSTRUTTIVA**

# Caratterizzazione meccanica del materiale costituente il nucleo

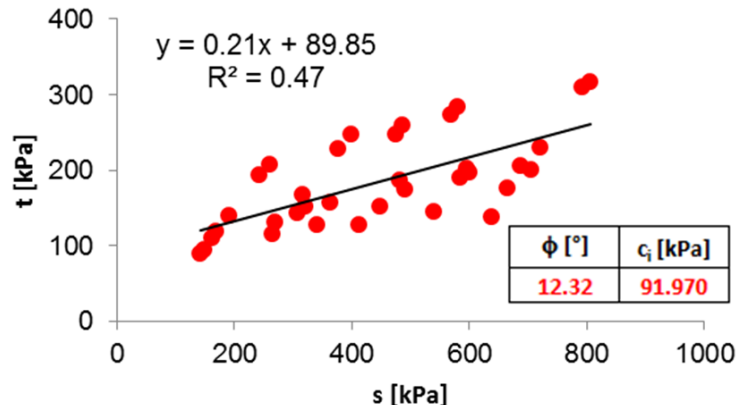
## Prove triassiali

(Laboratorio dell'Istituto di Tecnica delle  
Fondazioni e Costruzioni in Terra,  
Napoli, 1963)



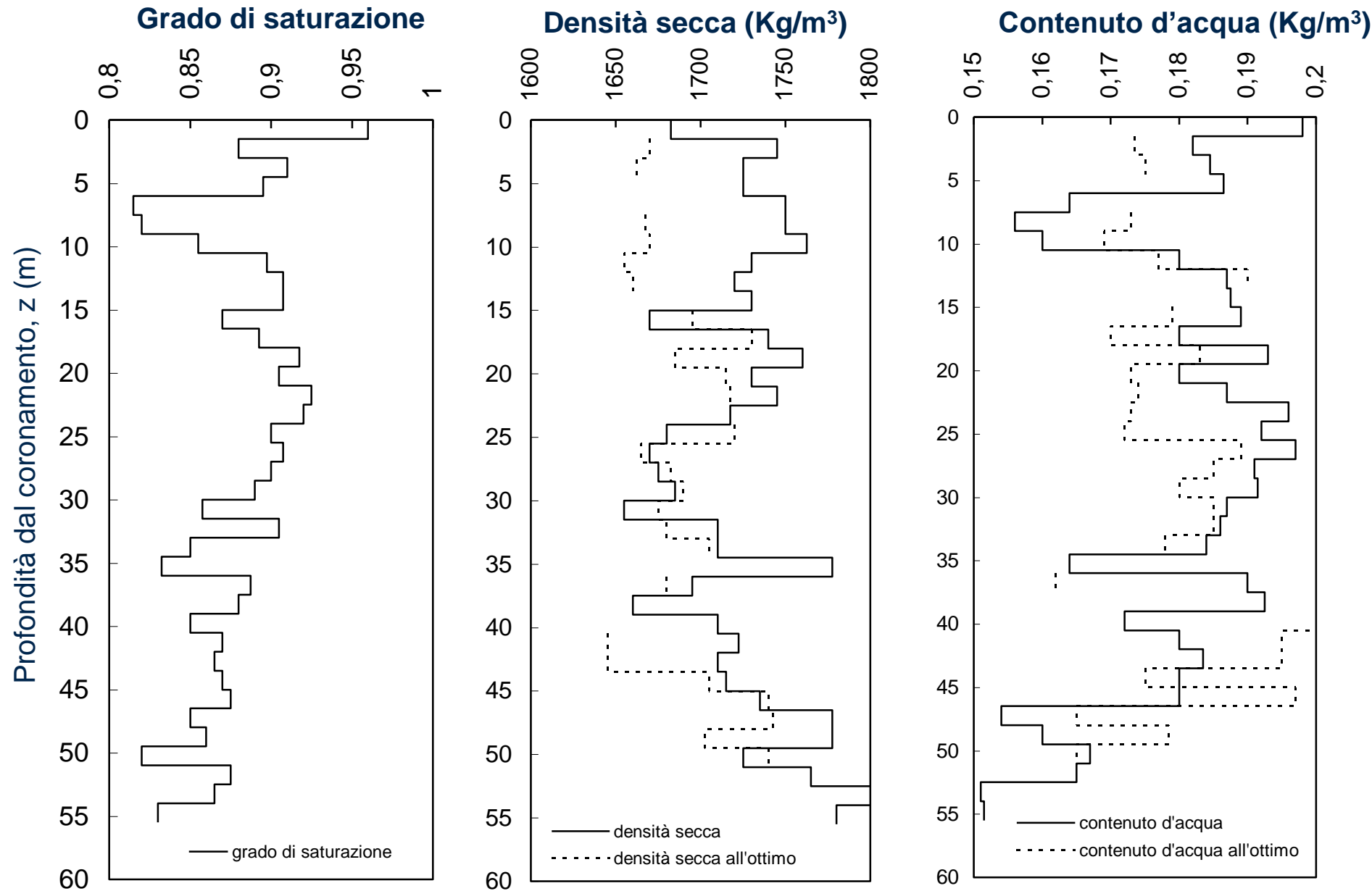
Prova	$\phi$ [°]	$c_i$ [kPa]
AN3-1	12.37	156.65
AN3-2	11.30	87.25
AN3-3	10.18	89.28
AN3-4	11.39	159.46
AN3-5	8.94	78.81
AN3-6	5.34	87.81
AN3-7	7.06	124.42

Interpolazione degli involuipi di  
resistenza



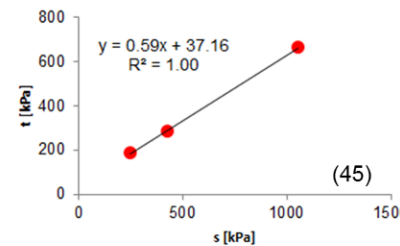
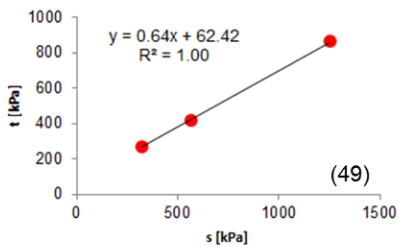
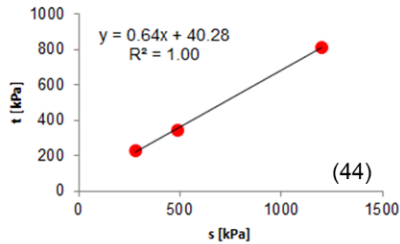
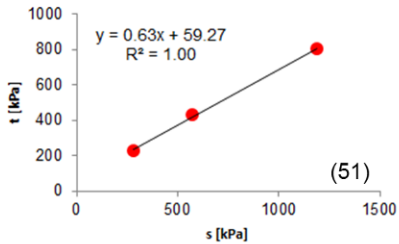
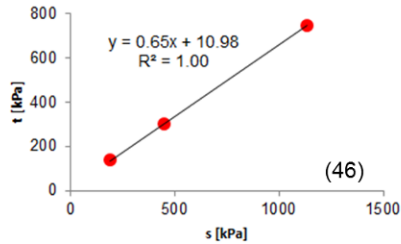
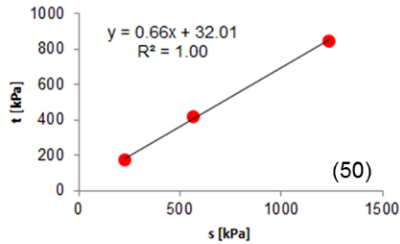
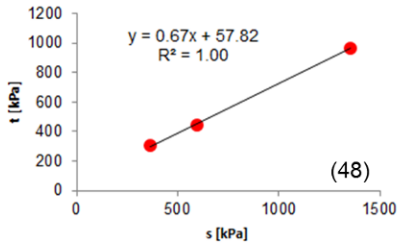
➤ Il termine coesivo è in larga misura  
generato dalla coesione apparente  
(depressione della fase liquida o  
suzione)

# Prove di controllo eseguite sul materiale costituente il nucleo



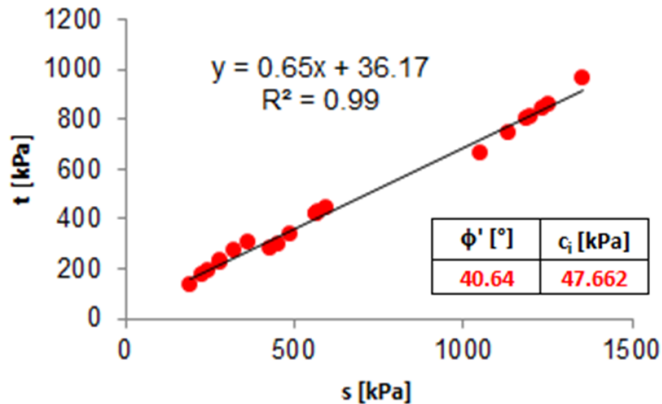
# Caratterizzazione meccanica del materiale costituente i fianchi

Prove triassiali  
(Laboratorio dell'Istituto di Tecnica delle  
Fondazioni e Costruzioni in Terra,  
Napoli, 1963)



Prova	$\phi'$ [°]	$c_i$ [kPa]
48	41.97	77.76
51	38.91	76.17
49	39.55	80.96
50	41.42	42.69
44	39.85	52.47
45	36.48	46.21
46	40.47	14.43

Interpolazione degli involuipi di  
resistenza

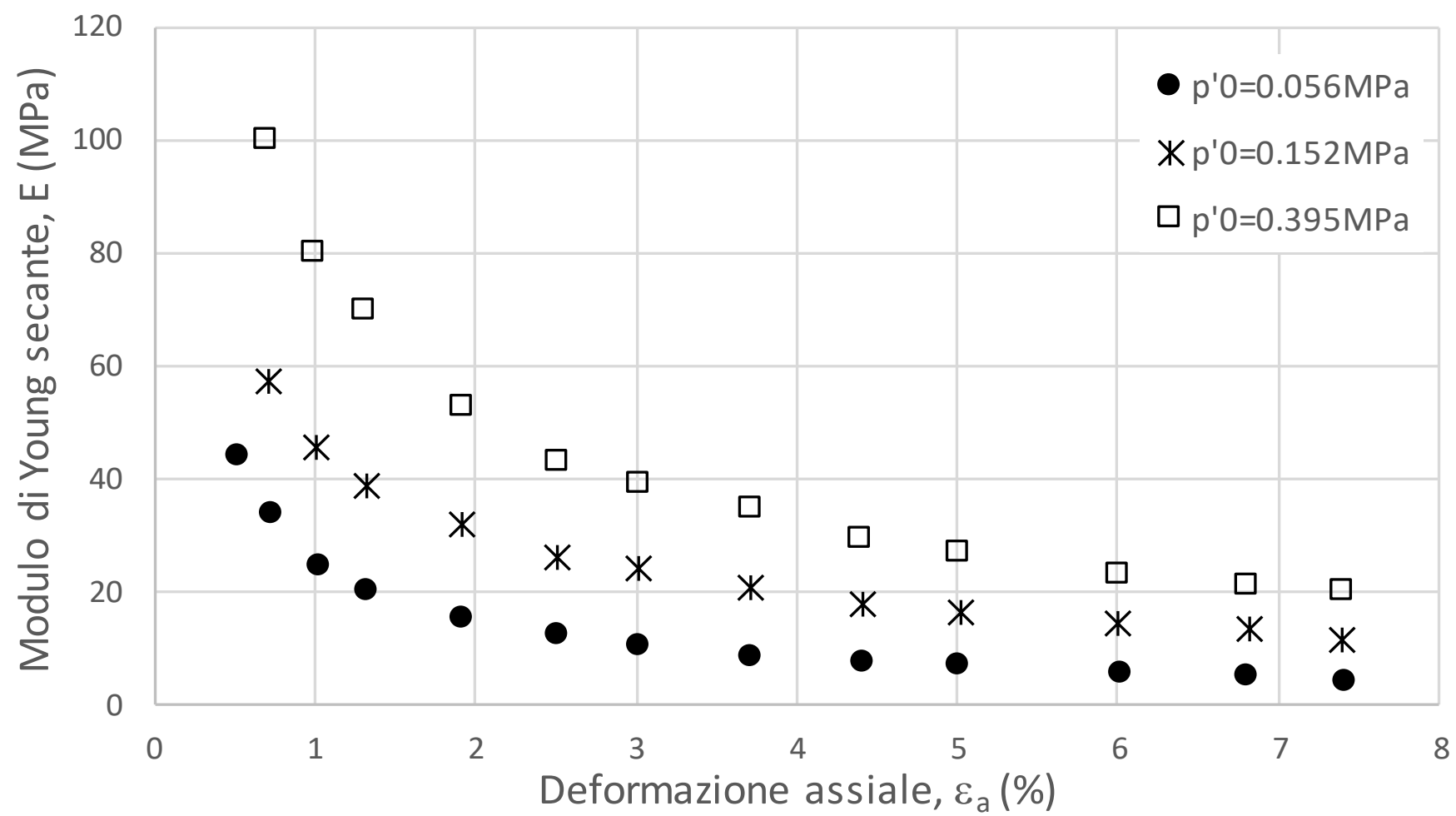


$\phi'$ [°]	$c_i$ [kPa]
40.64	47.662

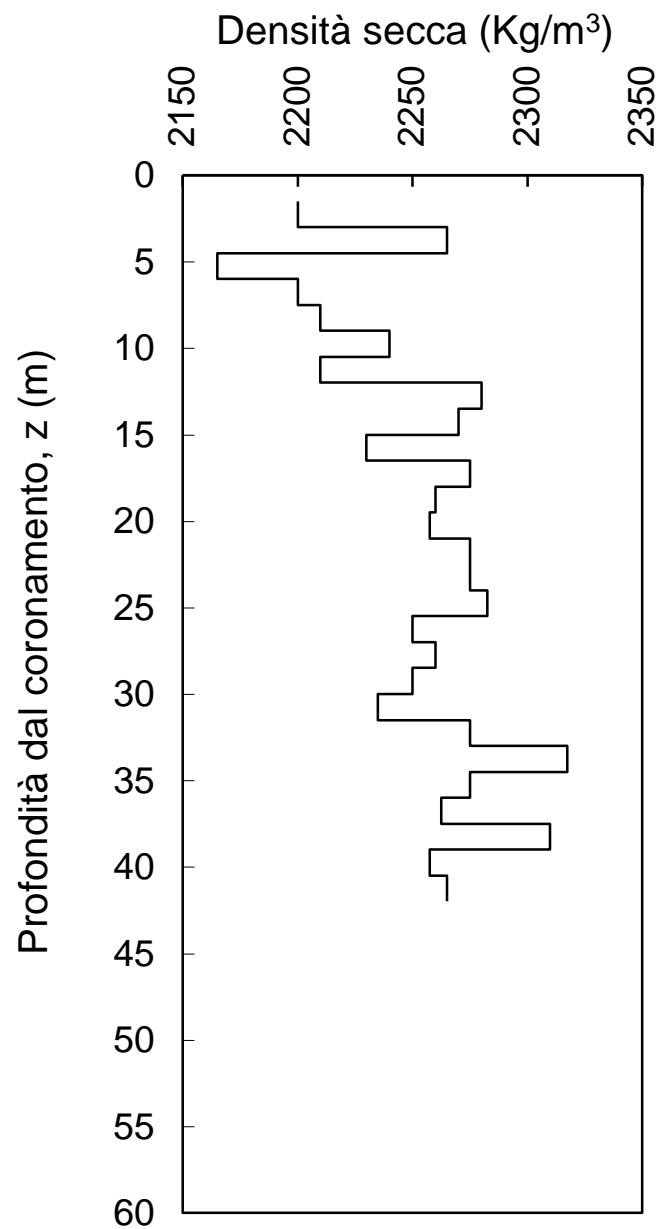


# Caratterizzazione meccanica del materiale costituente i fianchi

Prove triassiali  
(Laboratorio dell'Istituto di Tecnica delle  
Fondazioni e Costruzioni in Terra,  
Napoli, 1963)

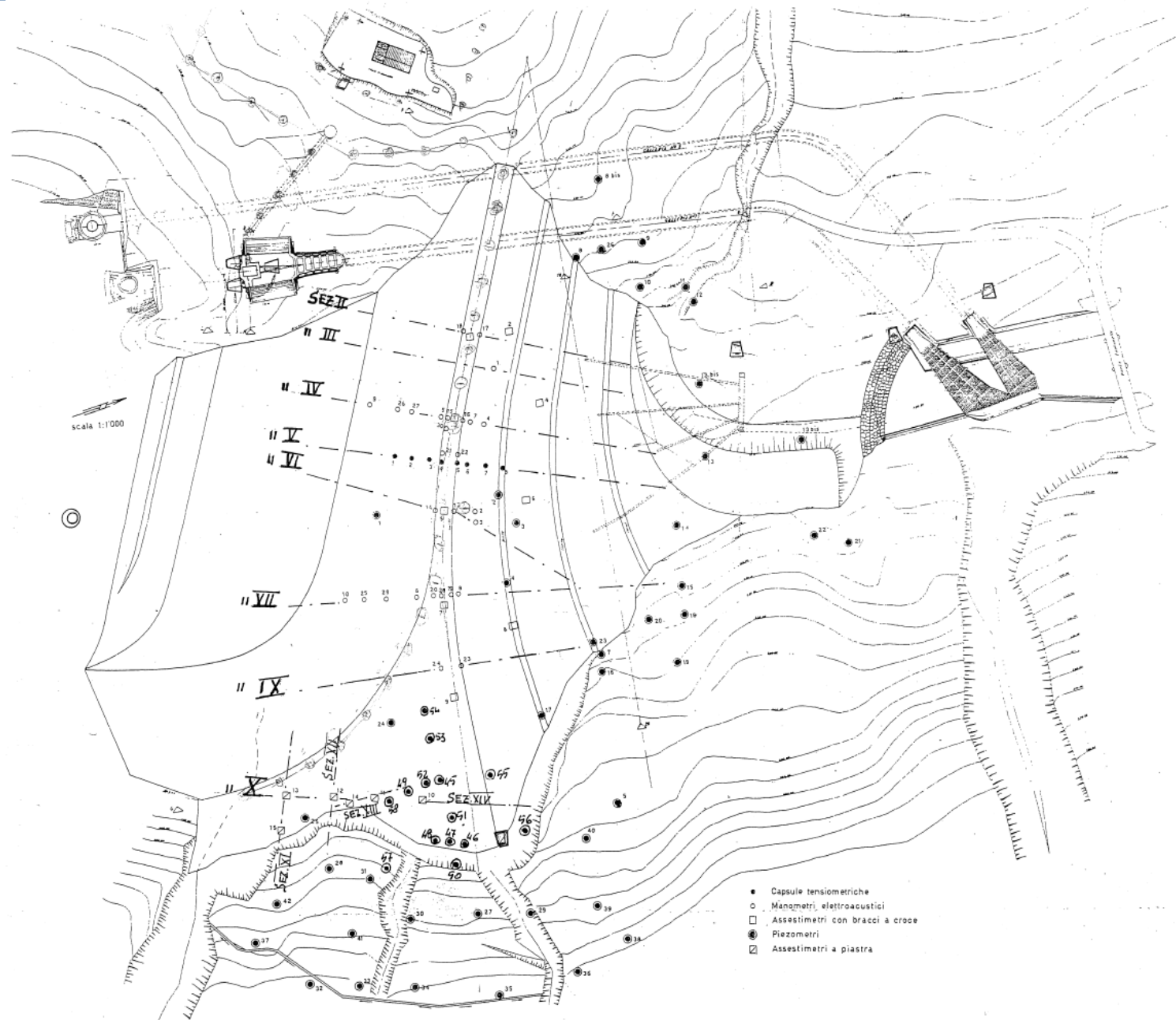


# Prove di controllo eseguite sul materiale costituente i fianchi



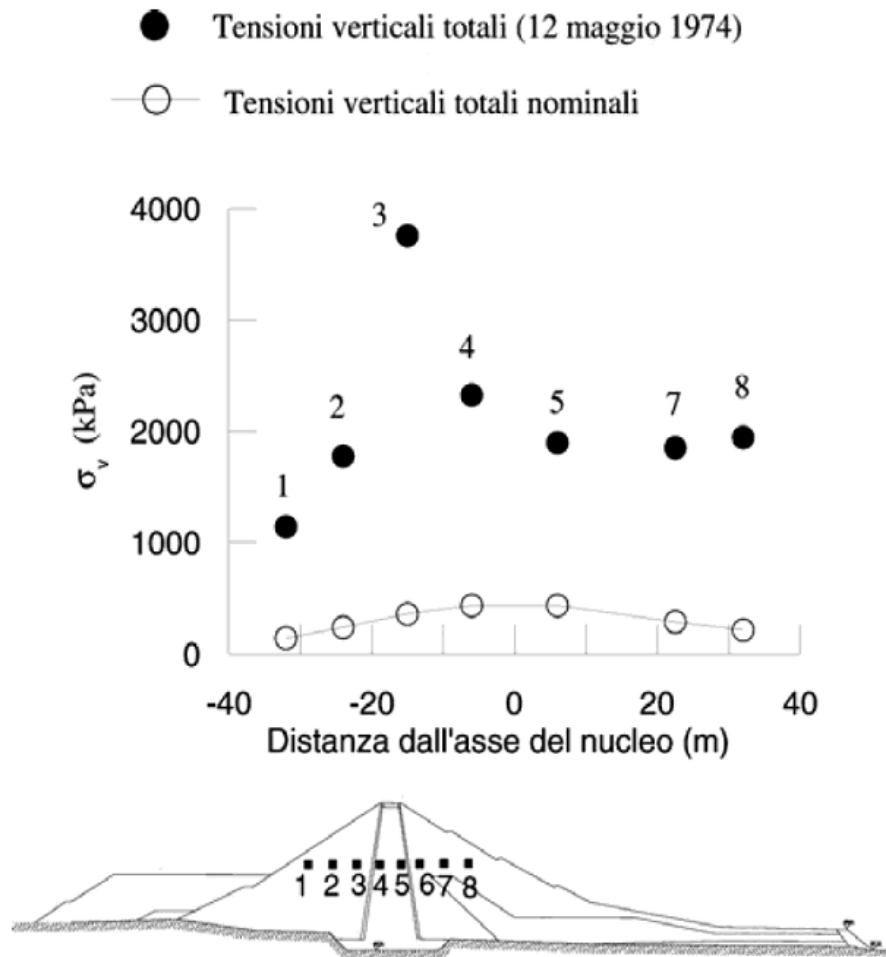
**DOCUMENTAZIONE DISPONIBILE DAL MONITORAGGIO  
STATICO DELL'OPERA**

# Ubicazione della strumentazione

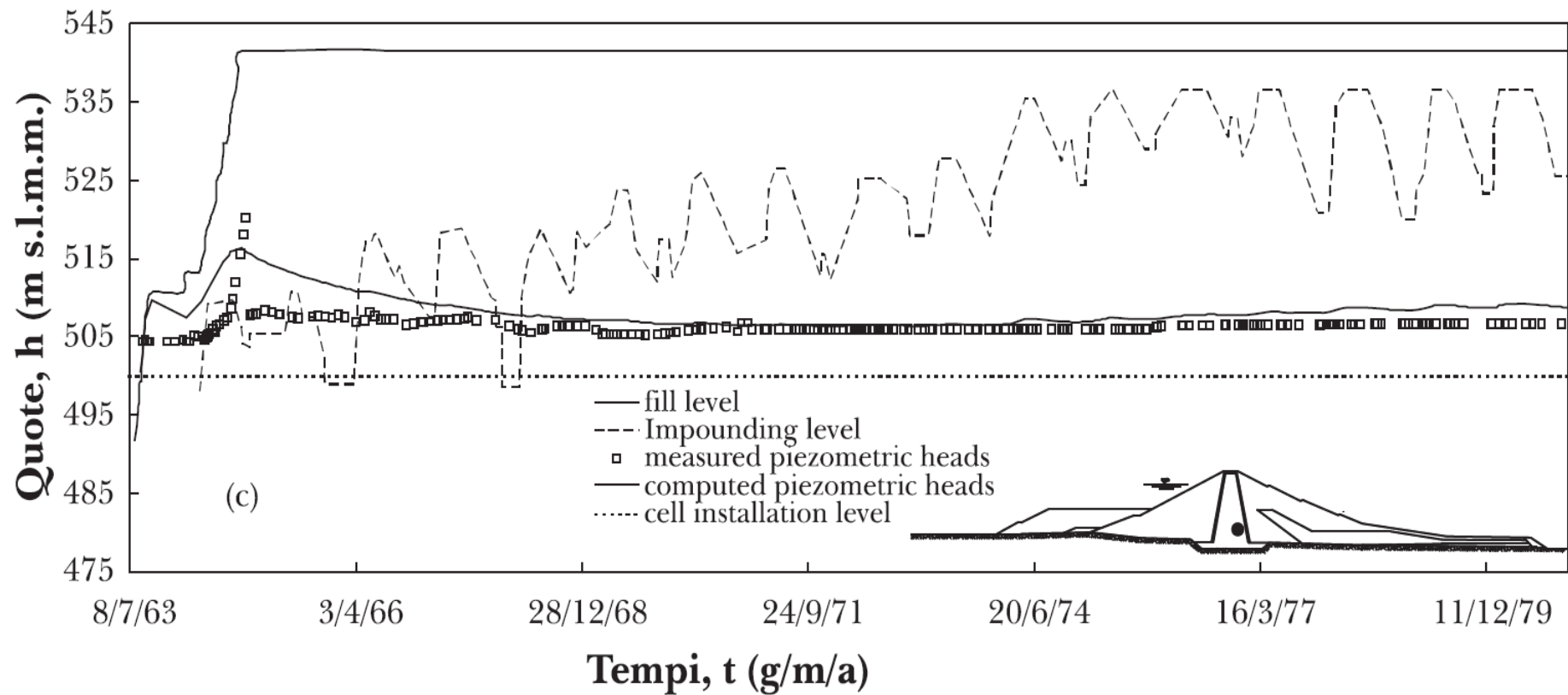




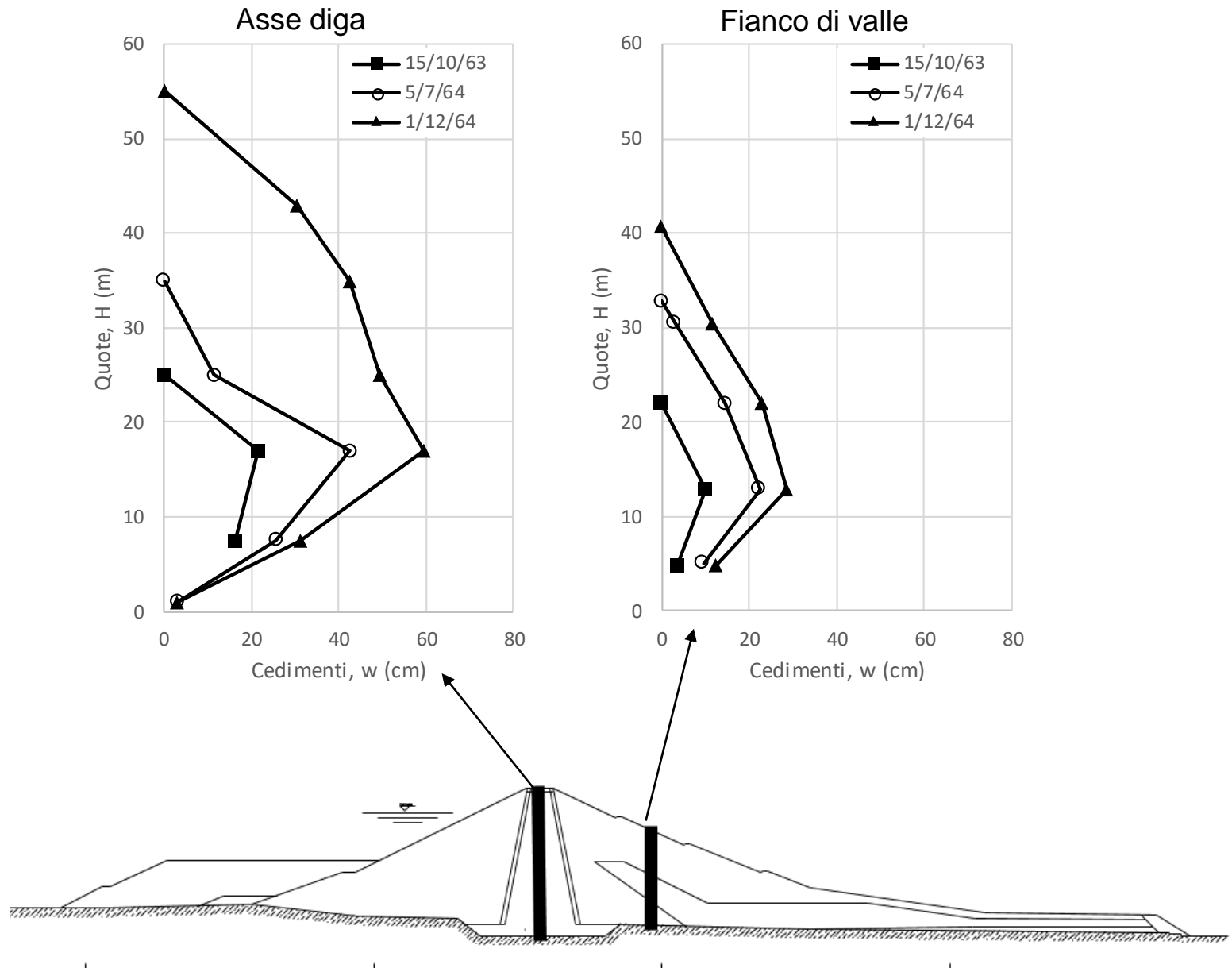
# Misure di tensioni verticali



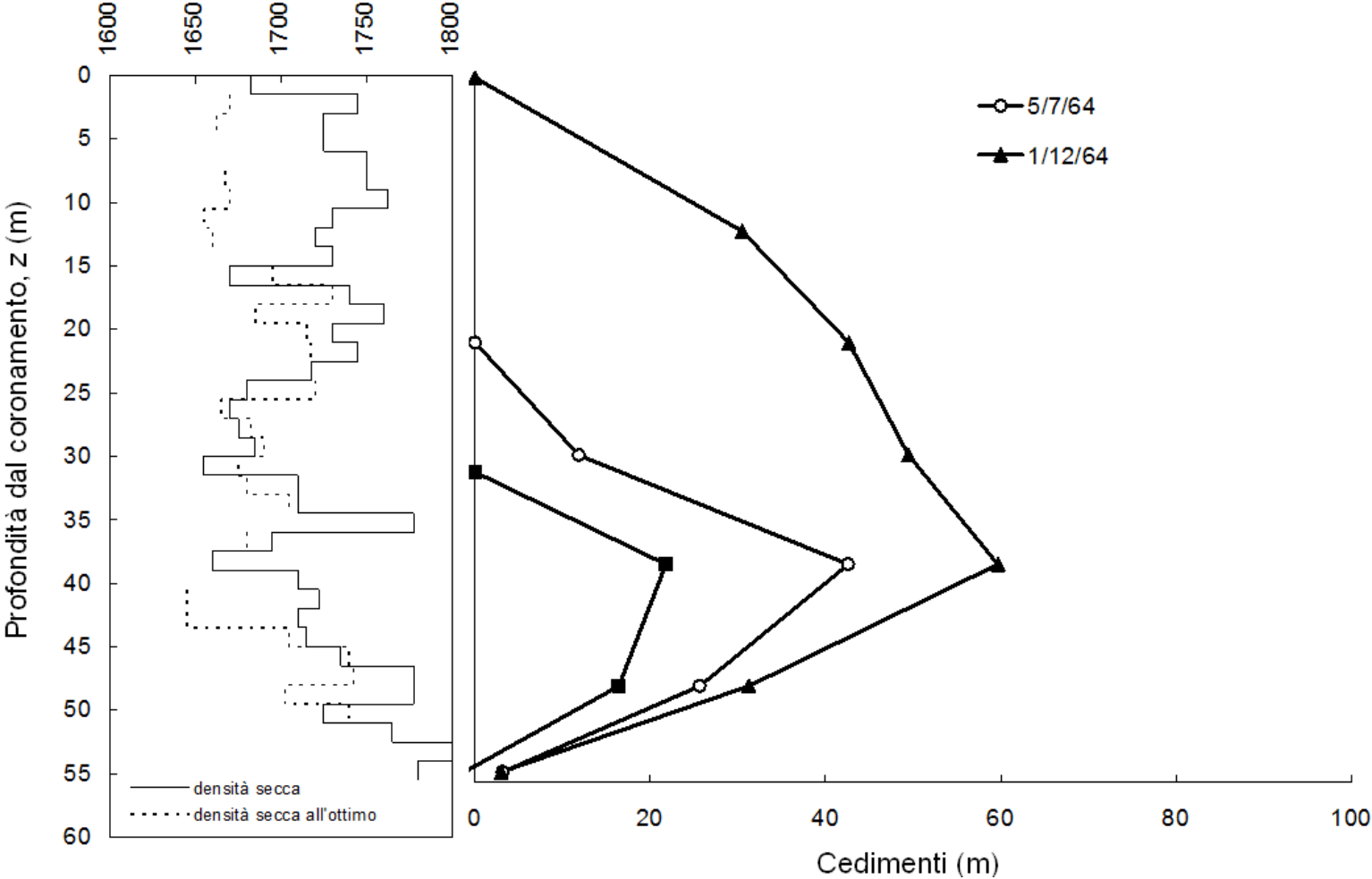
# Misure di pressioni interstiziali verticali



# Misure di cedimenti in fase costruttiva



# Misure di cedimenti in fase costruttiva





## **Comportamento della diga in corrispondenza di eventi sismici**

# Eventi sismici che hanno interessato la diga

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## Irpinia 1980

$$M_w = 6,89 \pm 0,04$$

$$D = 69.6708 \text{ km}$$

## Basilicata 1990

$$M_w = 5,8$$

$$D = 24 \text{ km}$$

Sabetta e Pugliese (1987):

$$\log A = 0.306 M_w - \log (D^2 + 5.82)^{1/2} + 0.169 S_1 + - 0.19$$

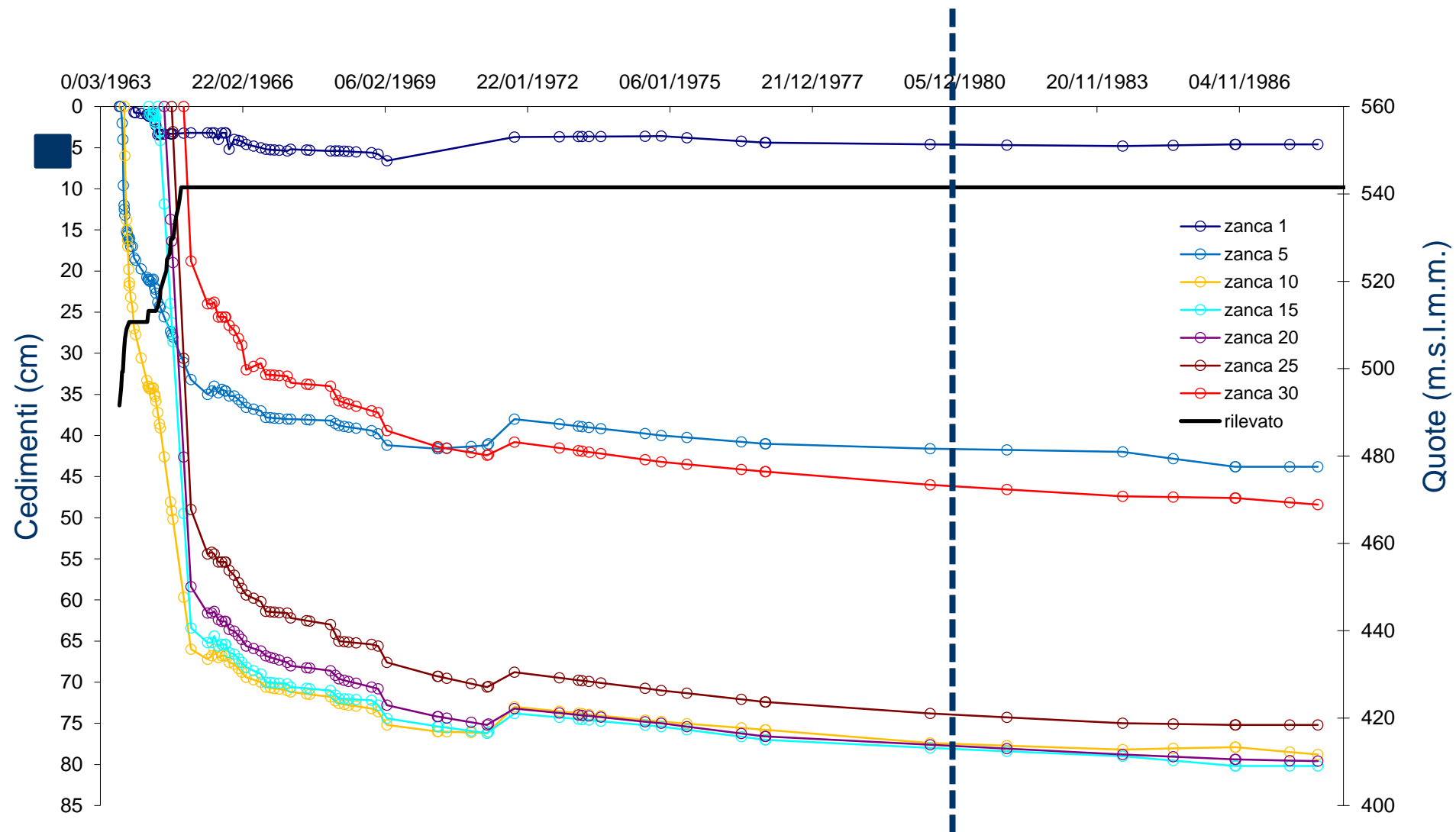
$S_1 = 0$ , (diga fondata sulla formazione rocciosa di base)

## Irpinia 1980

$$PGA = 0.03 - 0.08 \text{ g}$$

## Basilicata 1990

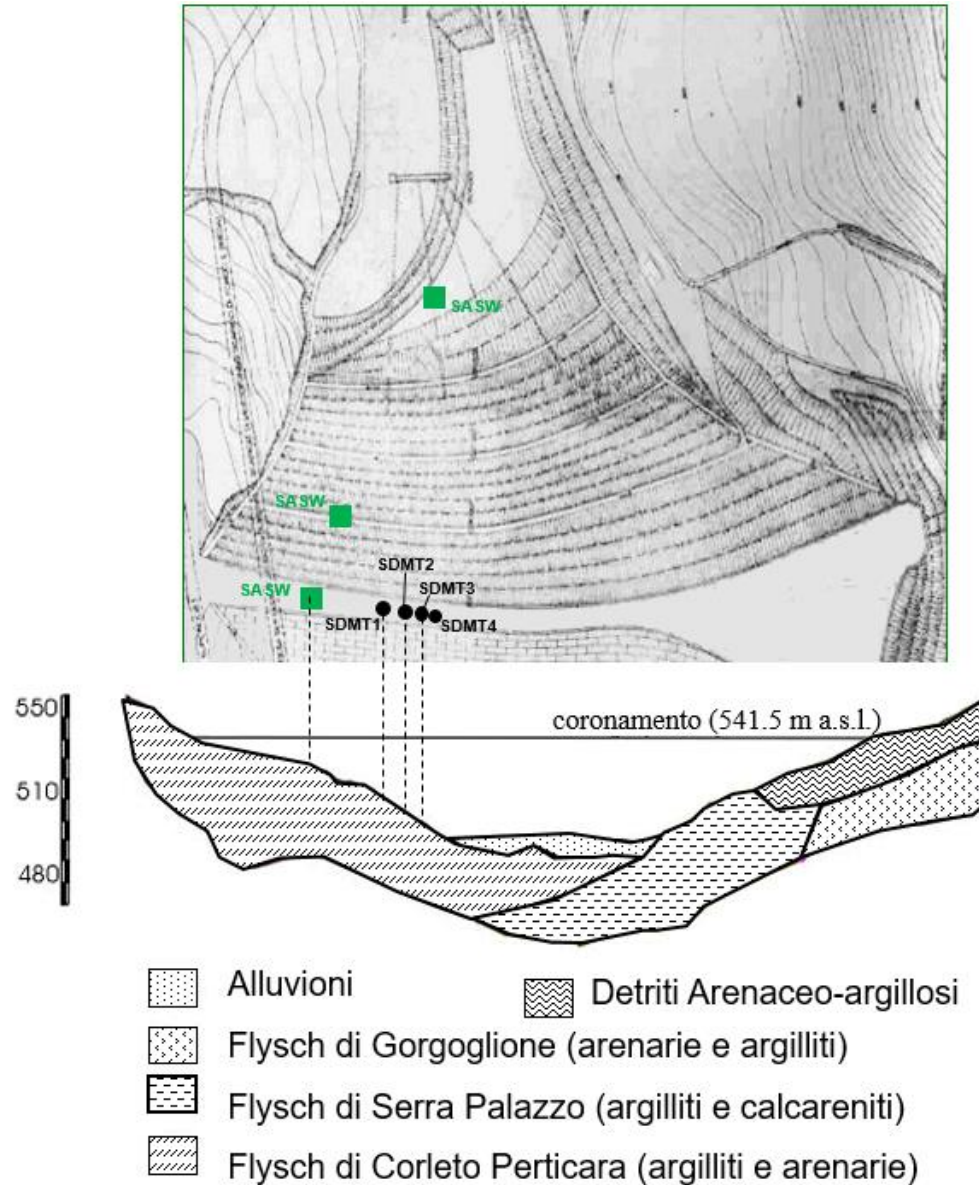
$$PGA = 0.04 - 0.1 \text{ g}$$



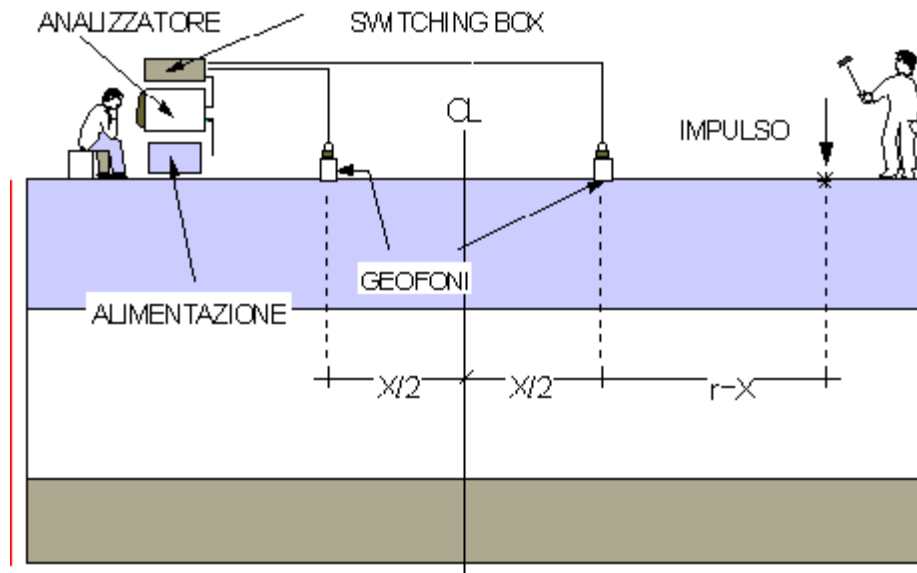
**PROVE INTEGRATIVE**



# Distribuzioni di $G_0$ e $G_{med}$

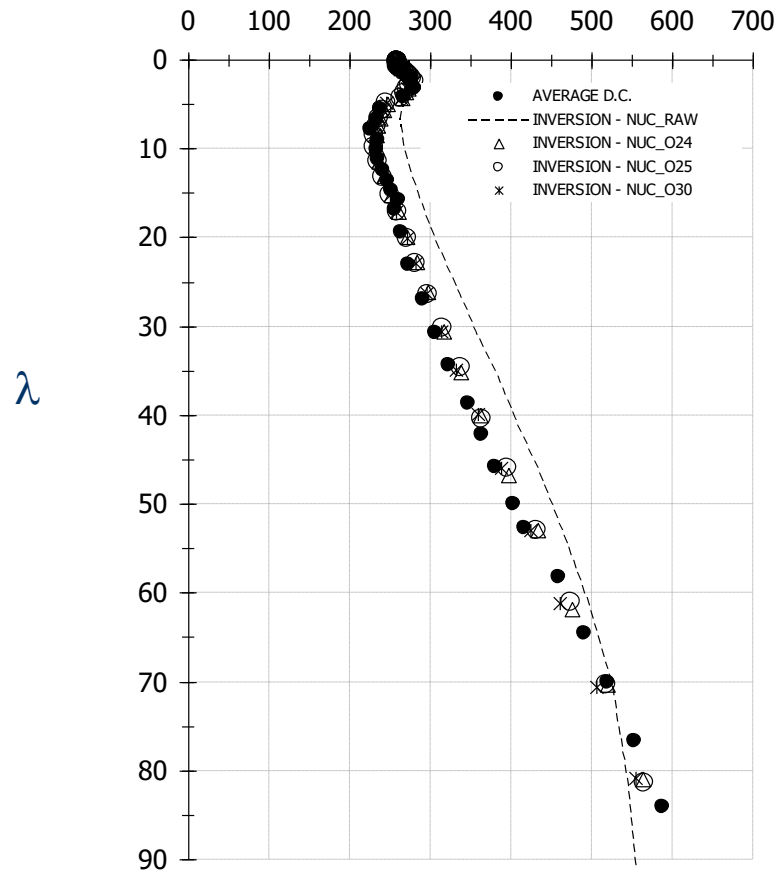


# Prove SASW



(Pagano, Mancuso, Sica2008)

## Velocita' delle onde di Rayleigh, $V_R$ (m/s)



# Prove SDMT



# Parametri della prova dilatometrica

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$E_D = 34.7(p_2 - p_1)$  modulo dilatometrico

$K_D = (p_1 - u_w) / \sigma'_{v0}$  Indice di sforzo laterale

$I_D = (p_2 - p_1) / (p_2 - u_w)$  Indice del materiale

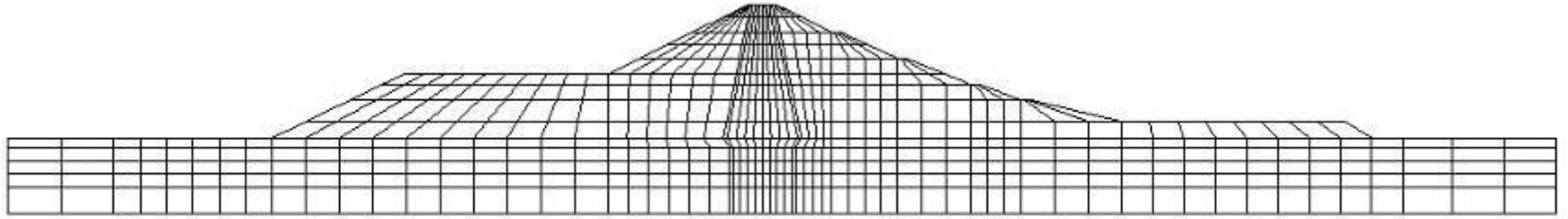
# Determinazione degli stati tensionali

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- L'interpretazione delle prove dilatometriche richiede la conoscenza degli stati tensionali
- Il modello utilizzato è basato su un approccio dinamico completo, calibrato nelle rigidità a grandi deformazioni per riprodurre il comportamento statico osservato



# ANALISI DEL PROBLEMA AL CONTORNO



## □ SISTEMA DI EQUAZIONI DIFFERENZIALI

EQUILIBRIO DINAMICO

CONGRUENZA

CONTINUITA' DELLA FASE LIQUIDA (termini inerziali)

LEGGE COSTITUTIVA DEL MEZZO (in tensioni efficaci)

## □ CONDIZIONI INIZIALI

STATI TENSIONALI EFFICACI

PRESSIONE DELLA FASE LIQUIDA

VARIABILI DI STATO (dipendono dal legame costitutivo)

## □ CONDIZIONI AL CONTORNO

PESO PROPRIO

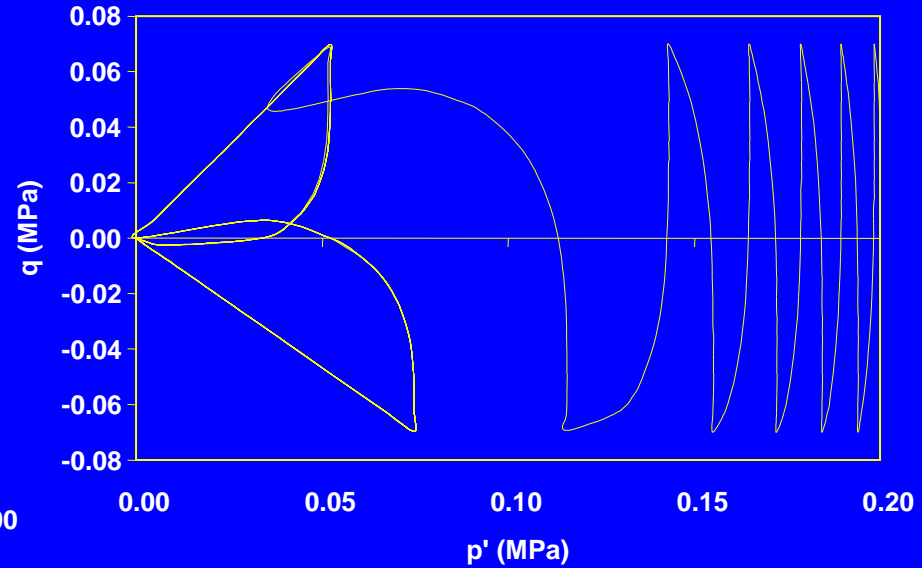
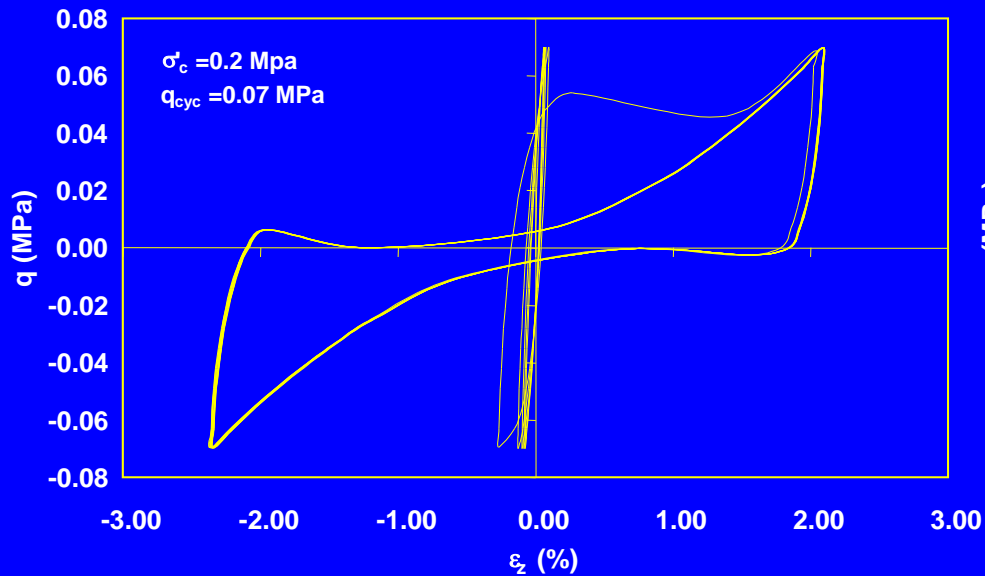
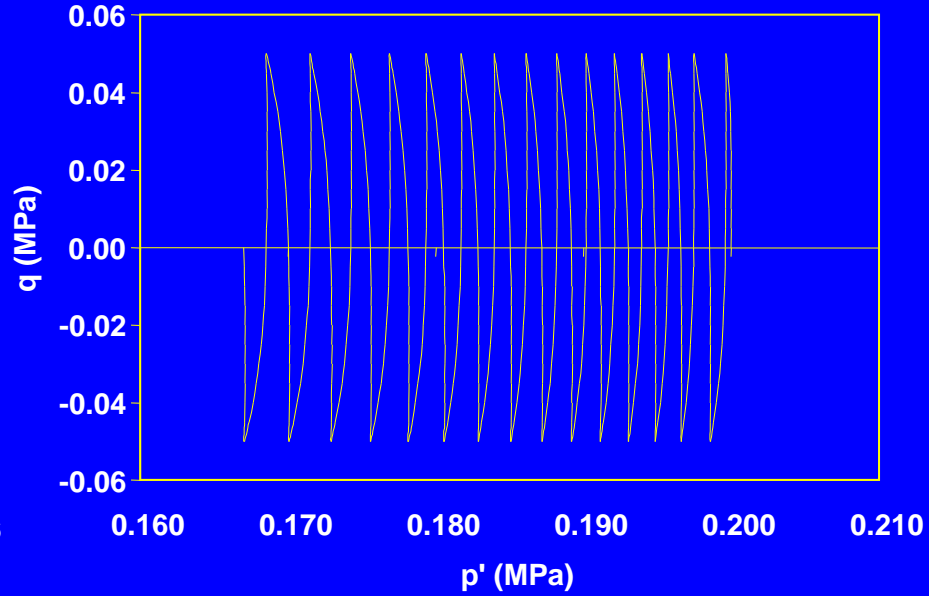
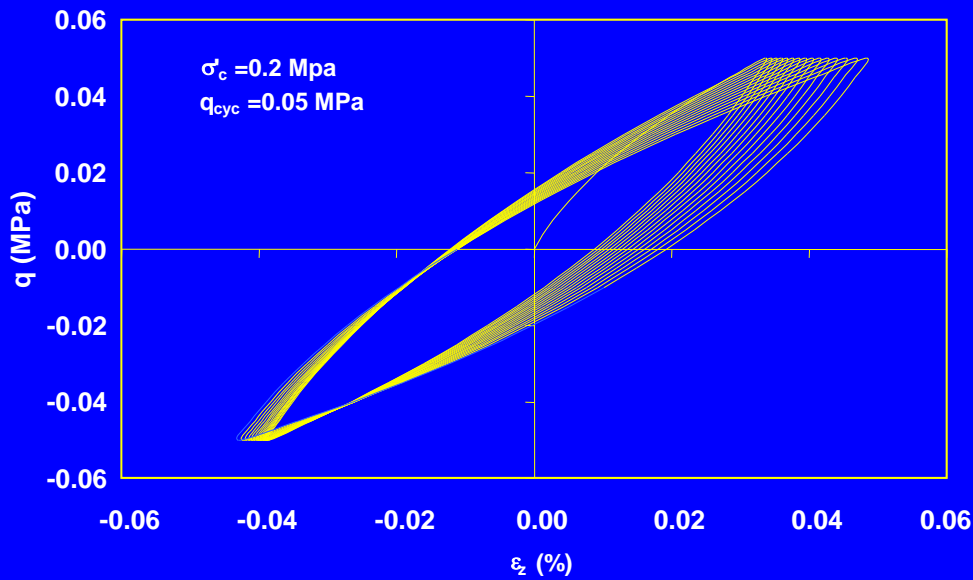
CONDIZIONI IDRAULICHE

STORIA DI ACCELERAZIONI

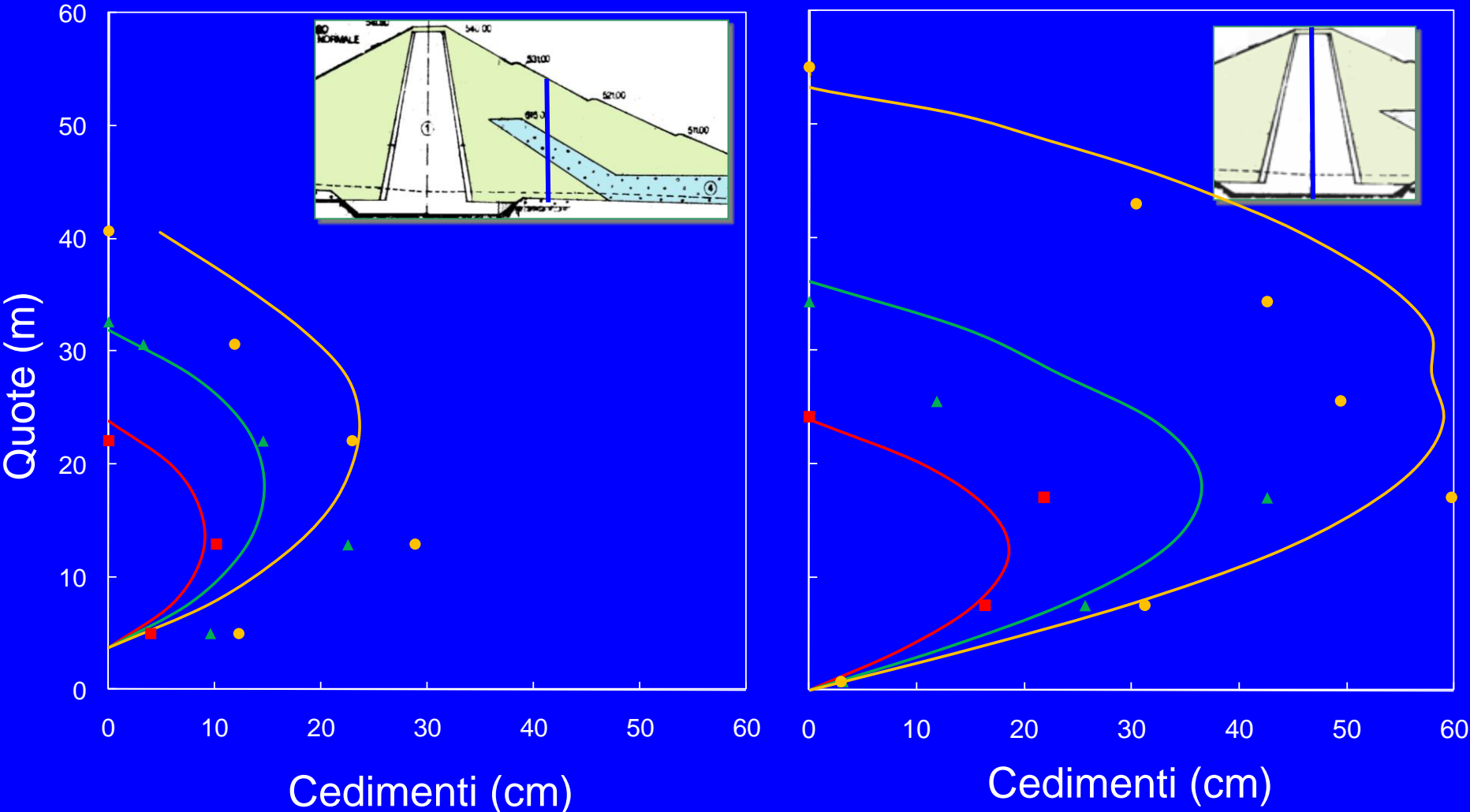
**L'EVENTO SISMICO E' CONTESTUALIZZATO ALL'INTERNO DELLE FASI STATICHE**



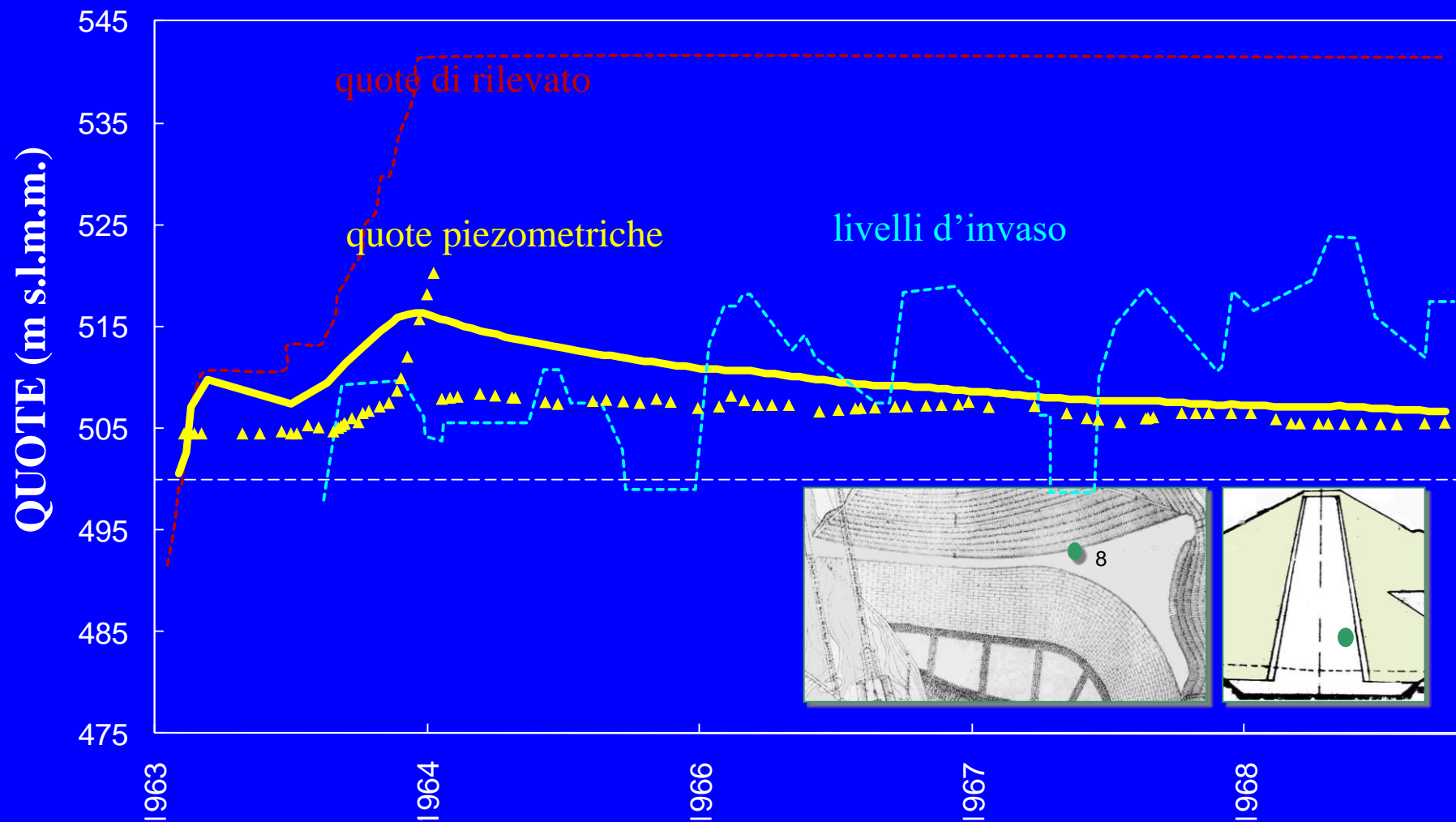
# Legame costitutivo di Hujeux (1985)



# Ricalibrazione dei parametri: cedimenti in fase costruttiva

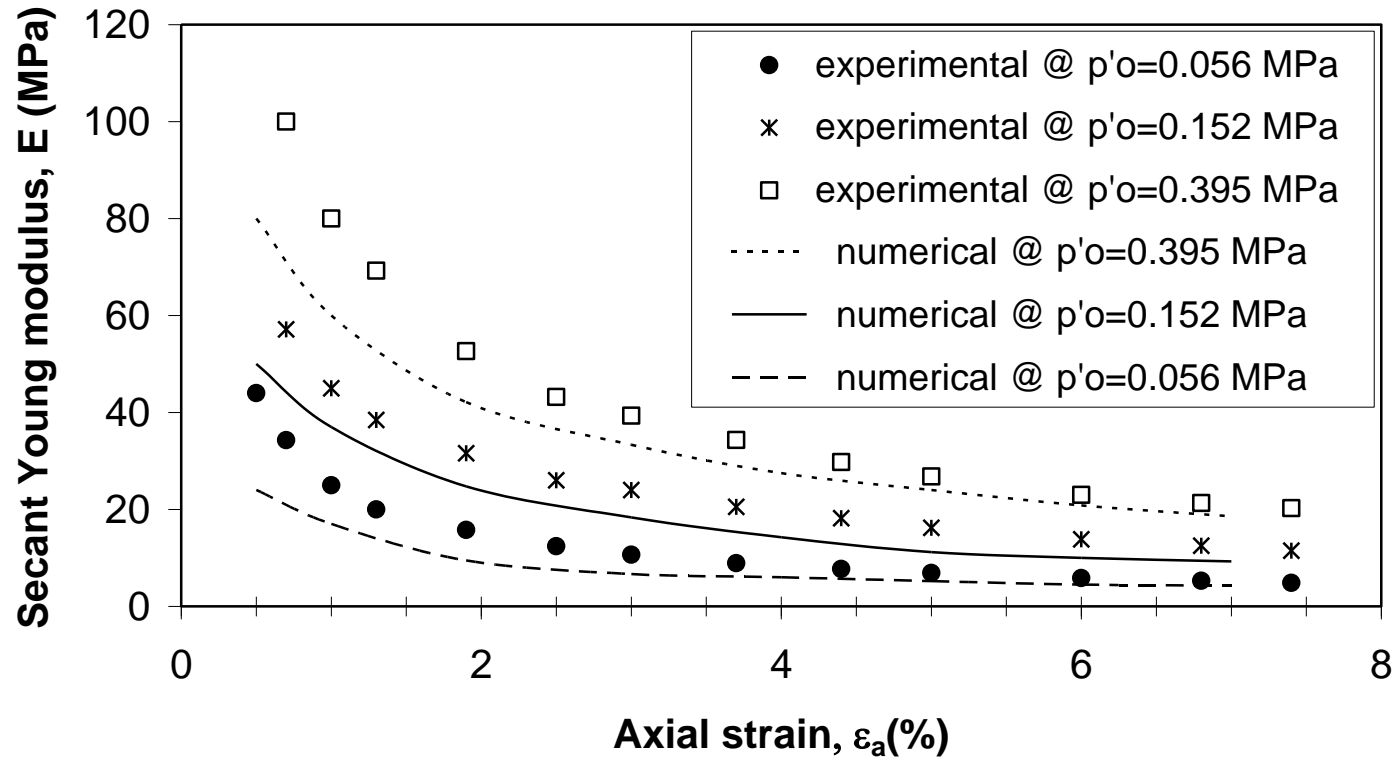


# Ricalibrazione dei parametri: quote piezometriche nel nucleo

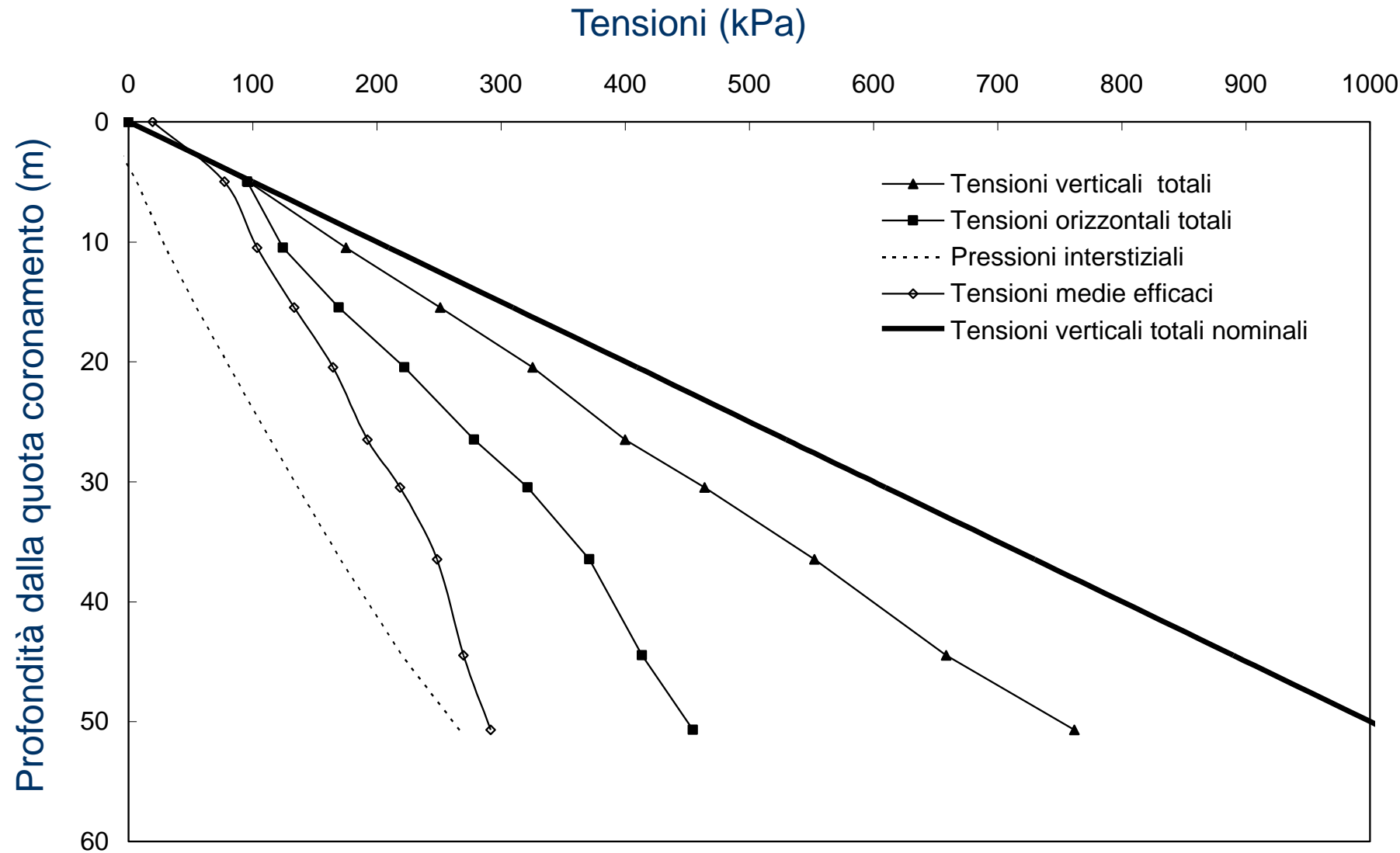


# Ricalibrazione delle rigidezze del materiale costituente i fianchi

Prove triassiali  
(Laboratorio dell'Istituto di Tecnica delle  
Fondazioni e Costruzioni in Terra,  
Napoli, 1963)

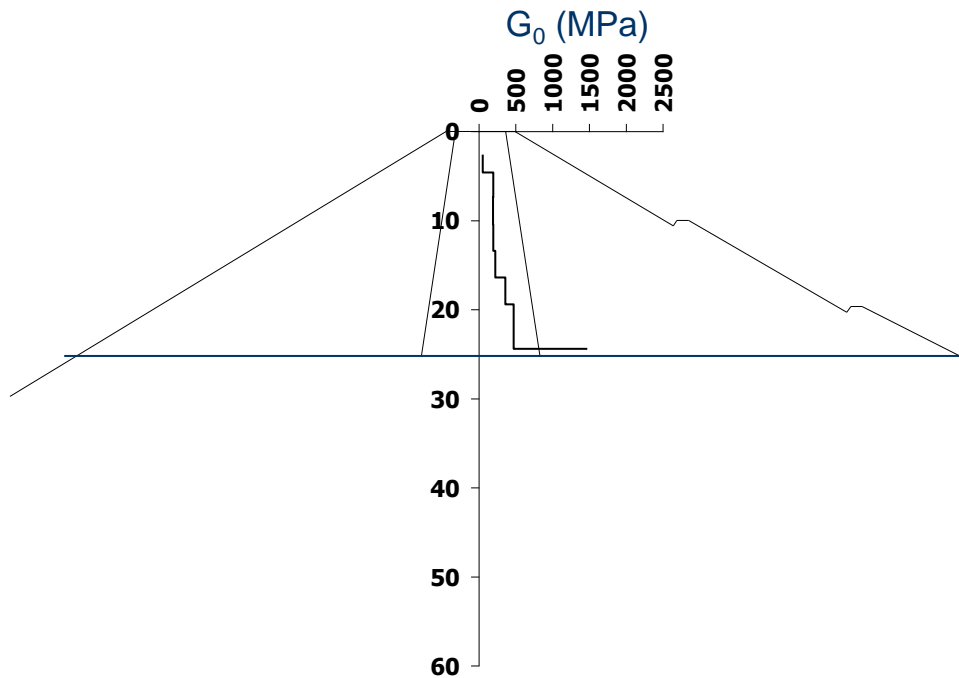
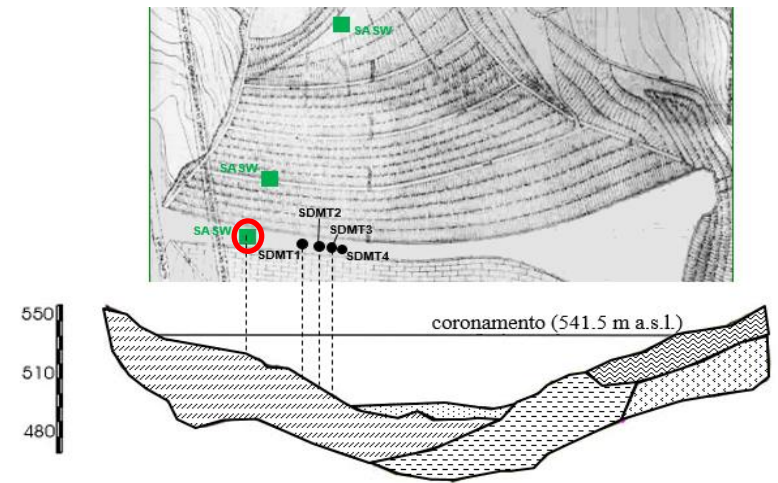


# Distribuzione degli stati tensionali nel nucleo



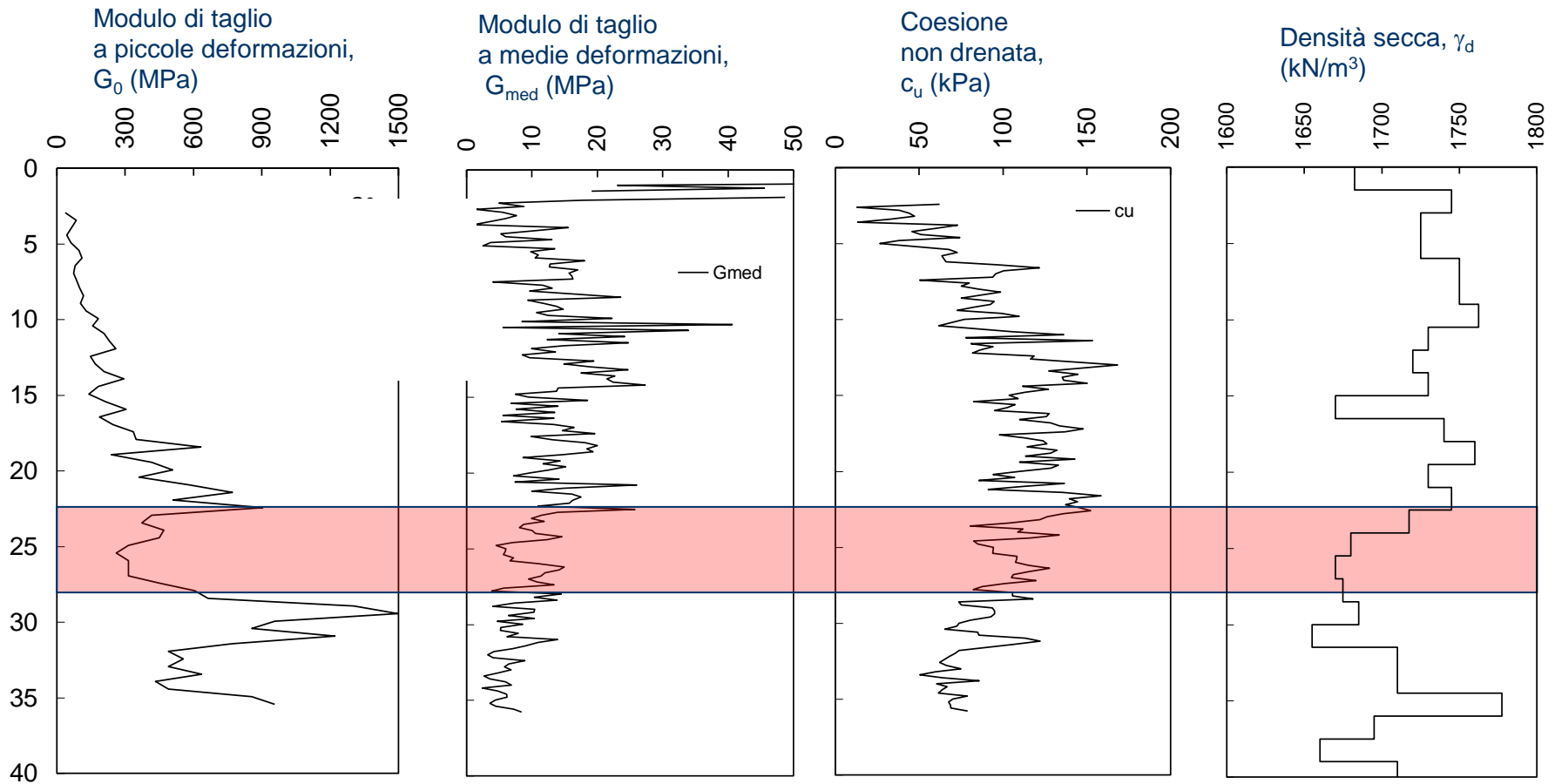
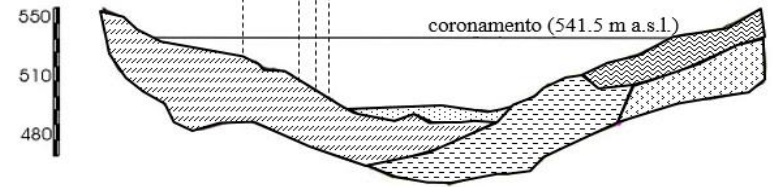
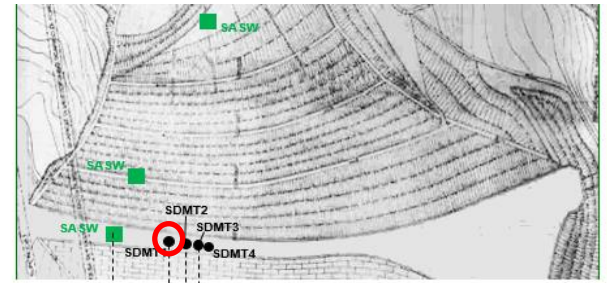
## **RISULTATI DELLE PROVE SASW E SDMT**

# Stendimento SASW nel nucleo

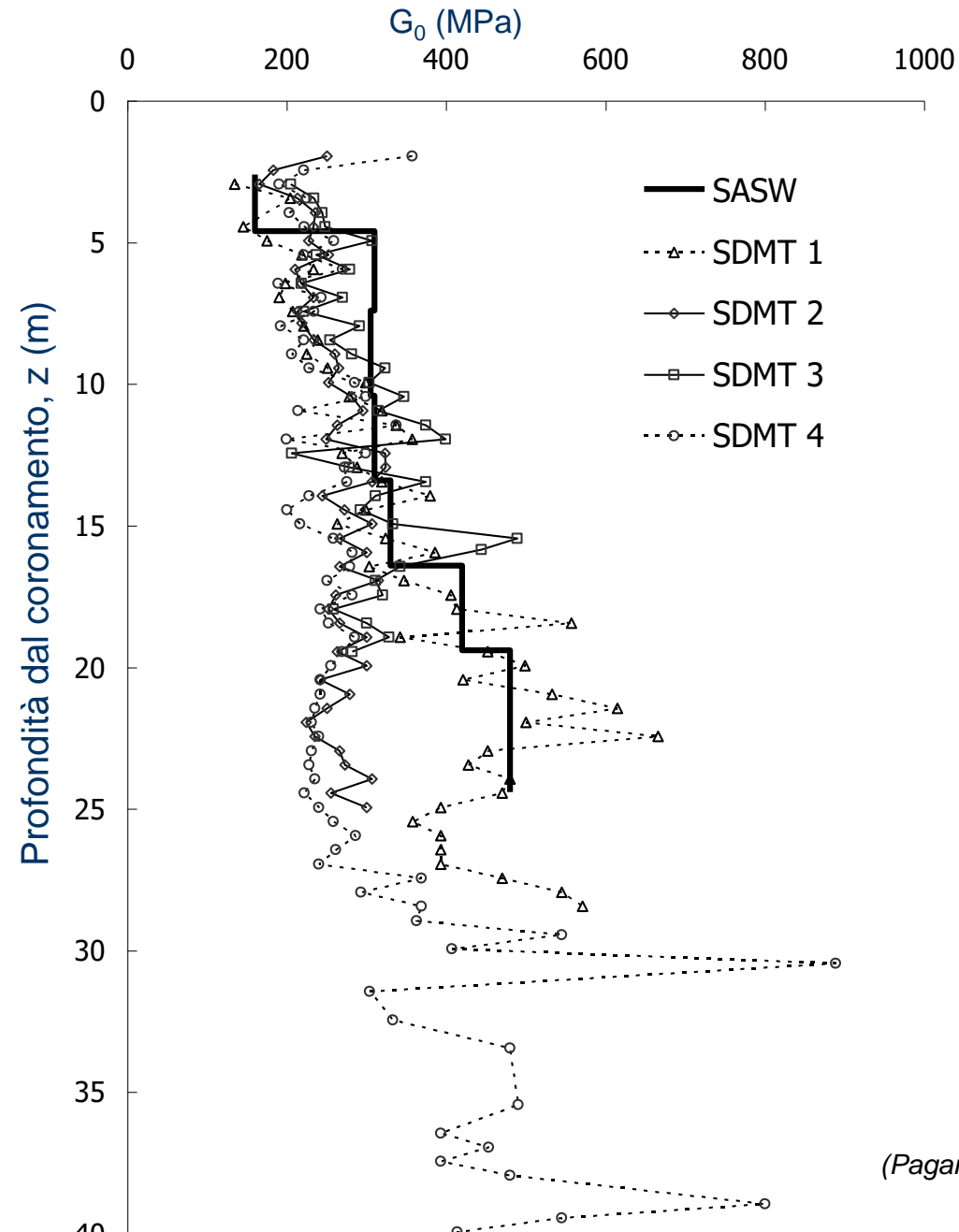




# SDMT1

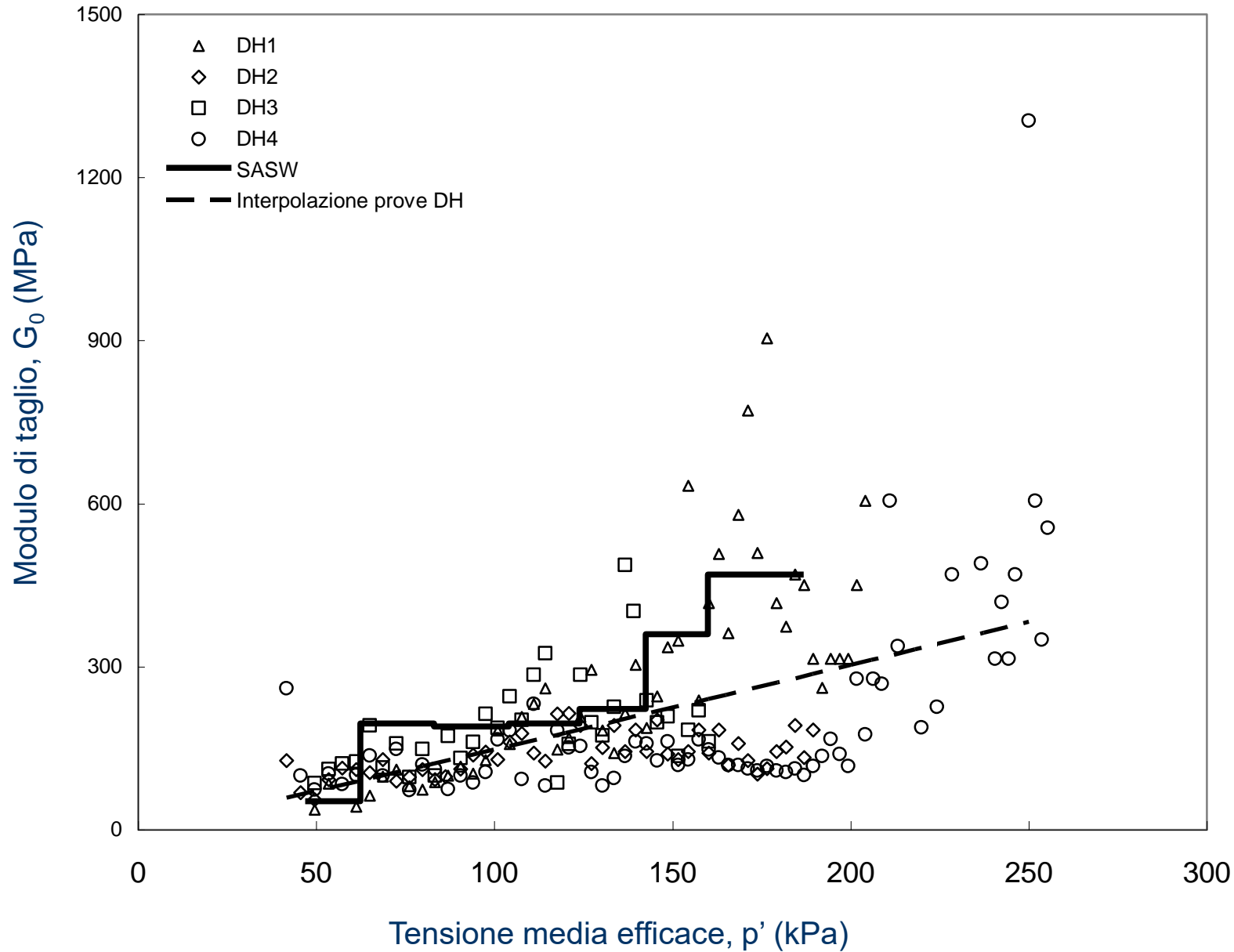


# Confronto dei risultati da prove SASW e SDMT

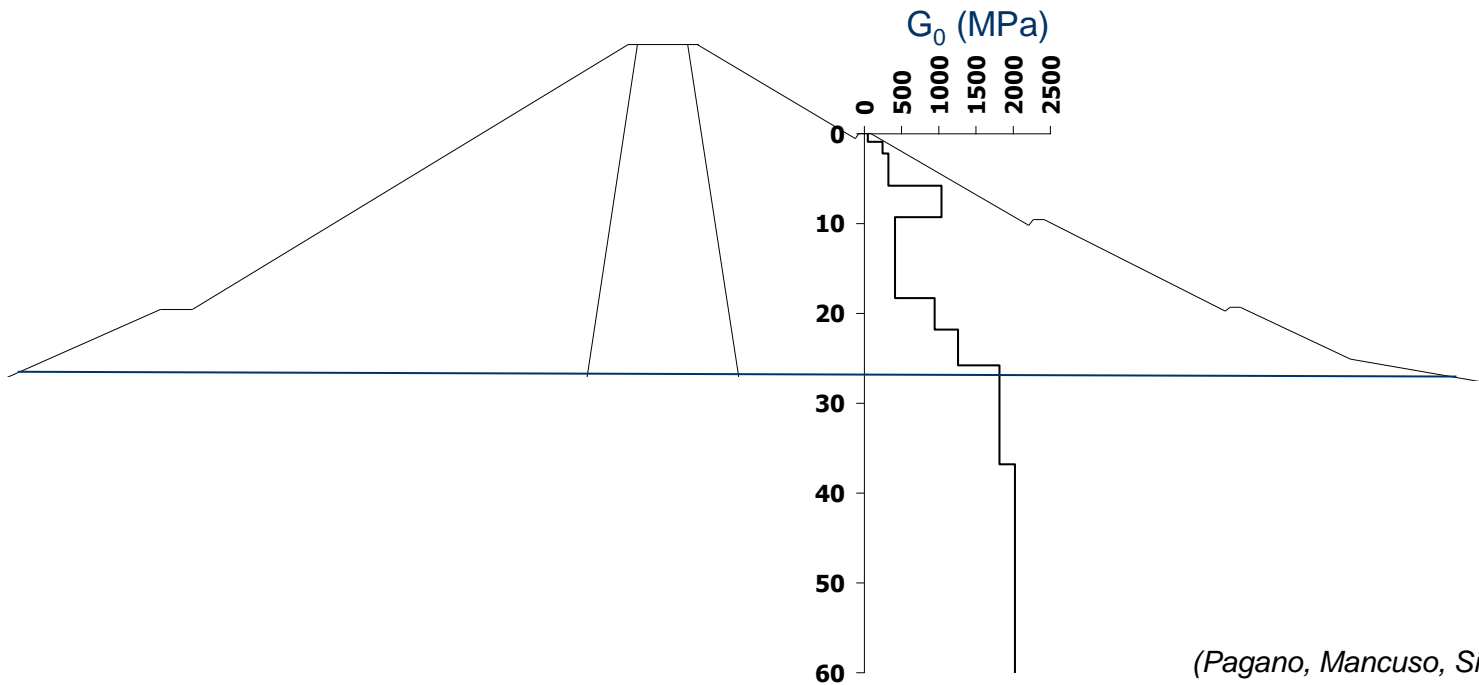
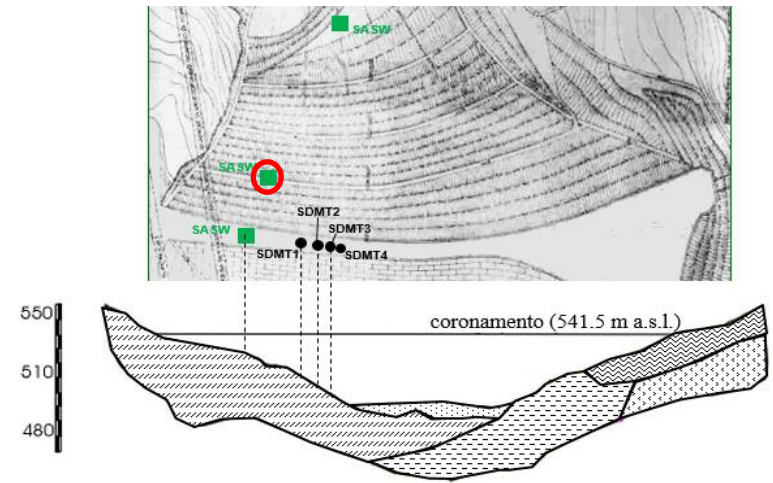


(Pagano, Mancuso, Sica, 2008)

# Relazione tra $G_0$ e tensione media efficace nel cuculo

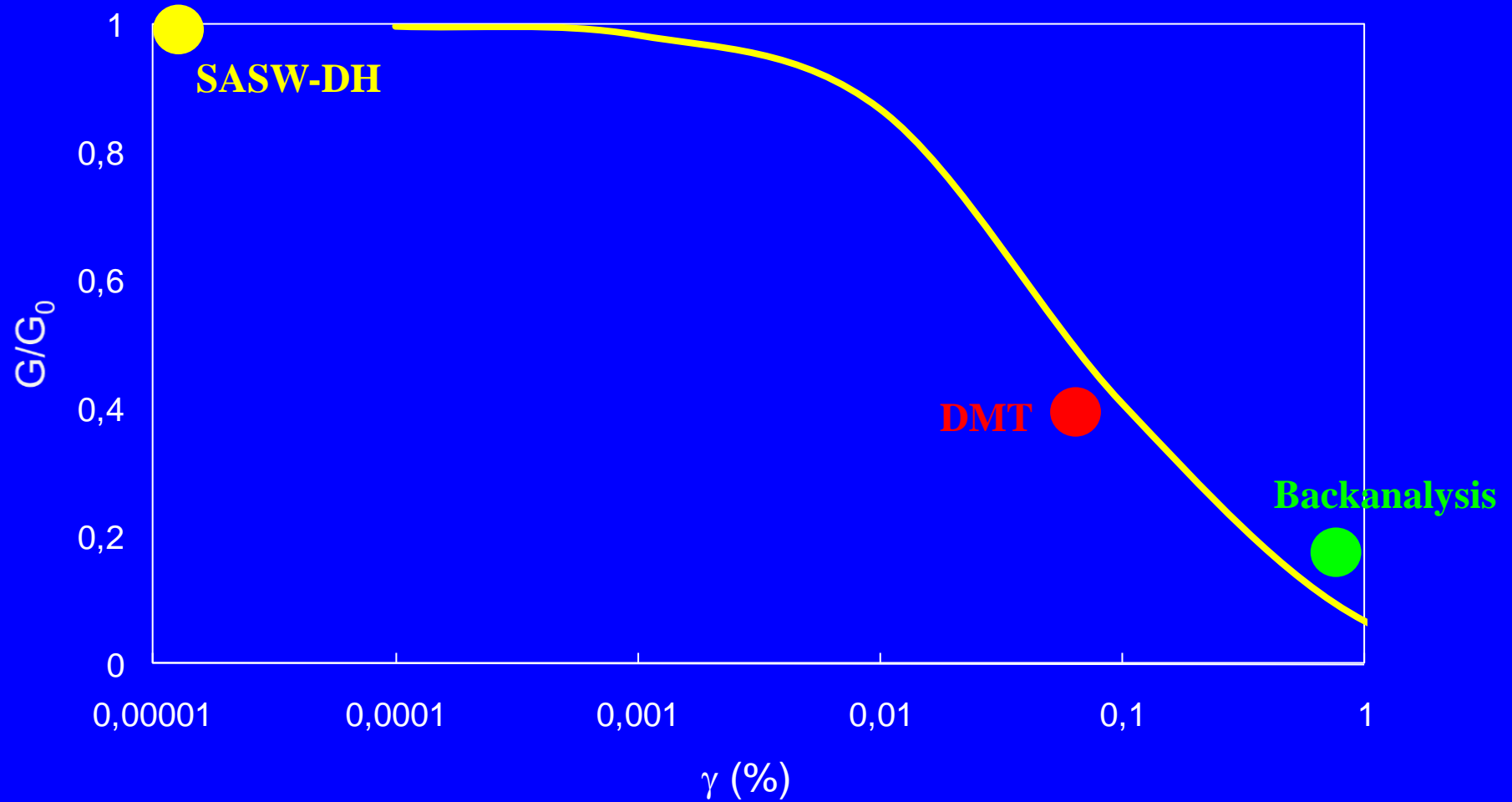


# Stendimento SASW nel fianco di valle



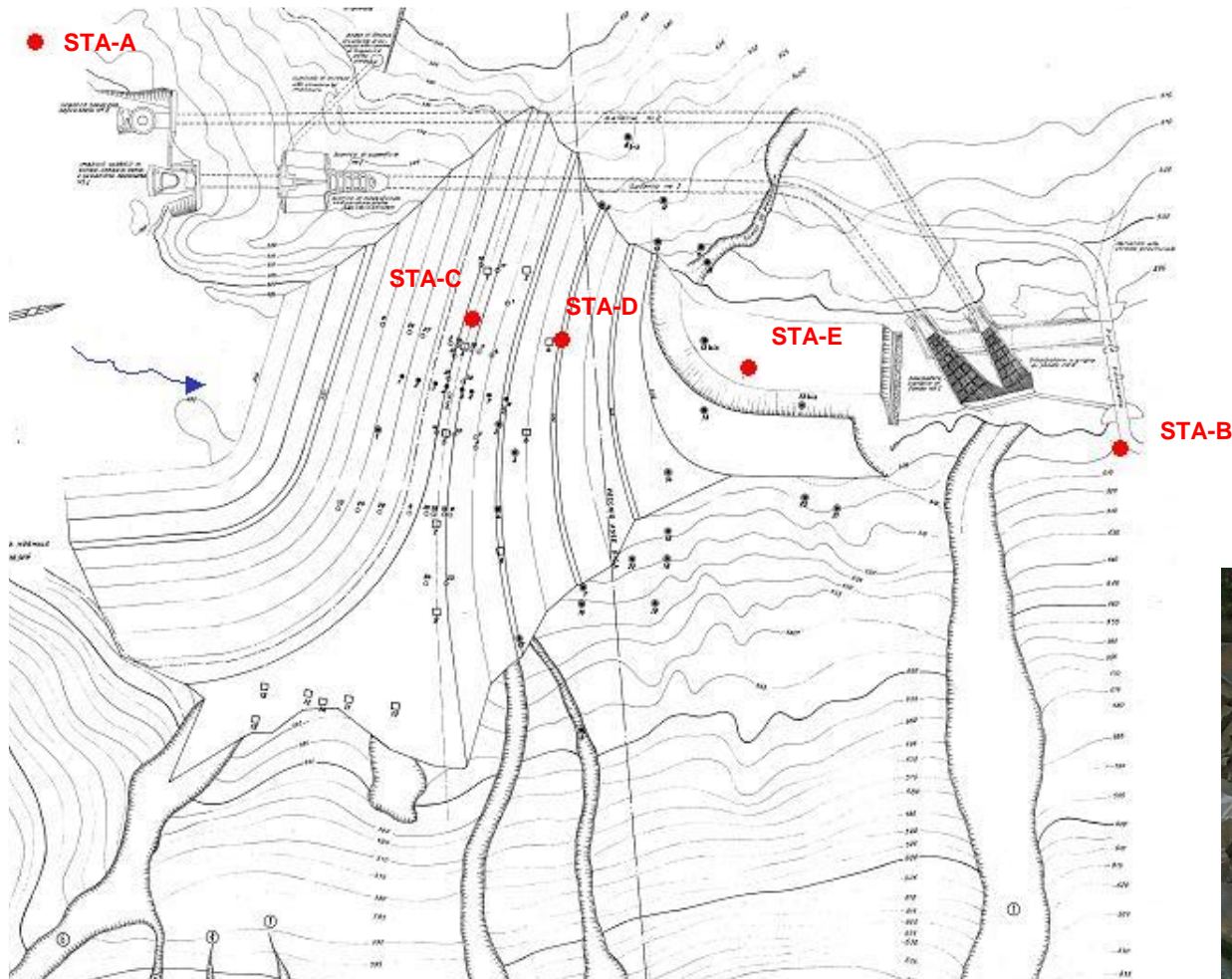
(Pagano, Mancuso, Sica, 2008)

# Decadimento del modulo di rigidezza a taglio



## **MONITORAGGIO INTEGRATIVO**

# Ubicazione delle stazioni accelerometriche



**STA-A: Affioramento roccioso  
(Corleto Perticara)**

**STA-B: Affioramento roccioso  
(Serra Palazzo)**

**STA-C: Coronamento diga**

**STA-D: Banchina intermedia del  
paramento di valle**

**STA-E: Base del paramento di  
valle**



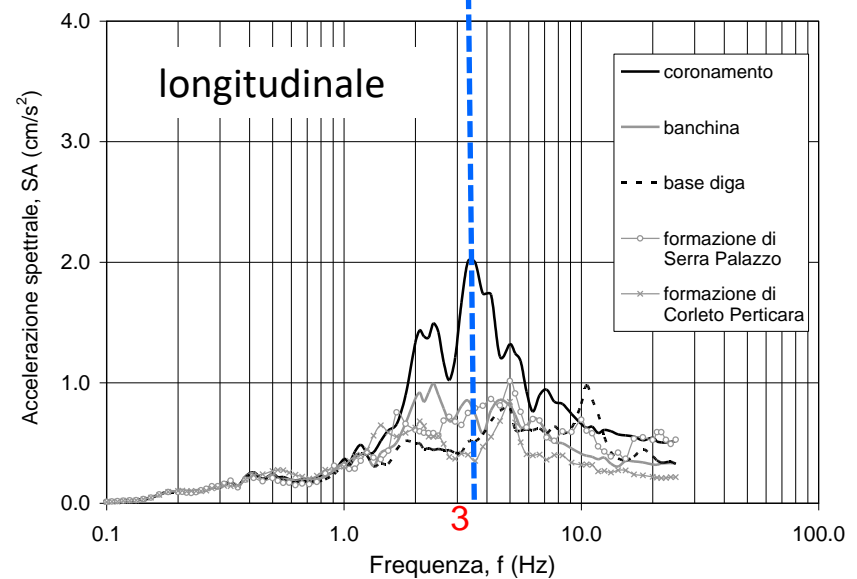
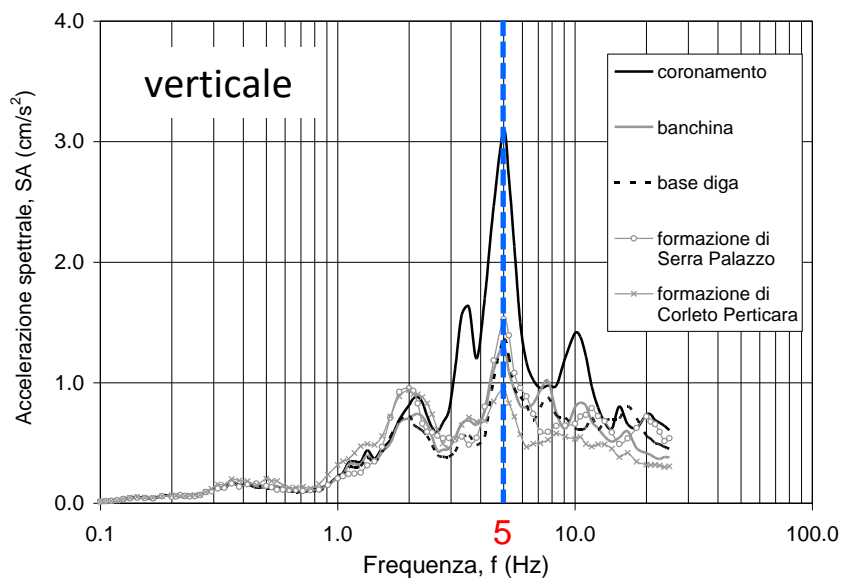
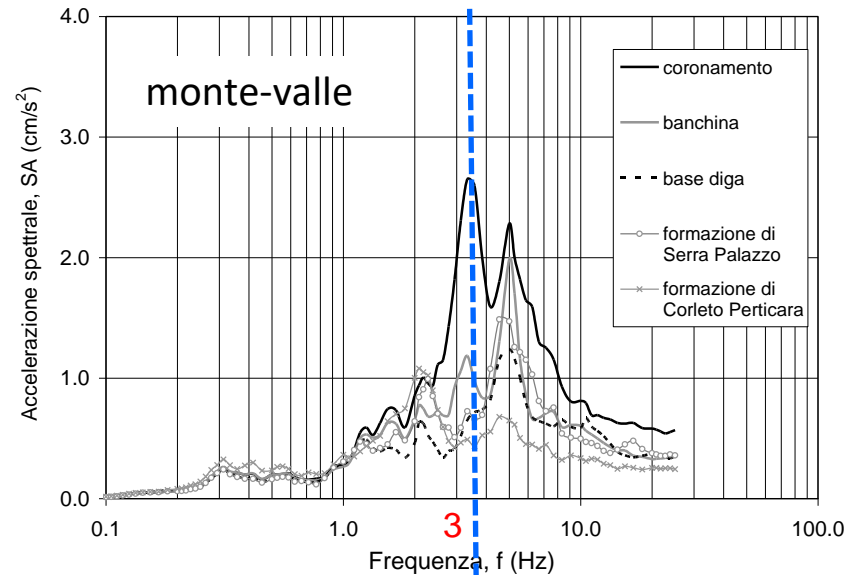
*(Sica, Pagano, Vinale, 2008)*



# Registrazione di eventi *far-source*

## EVENTO FAR-SOURCE

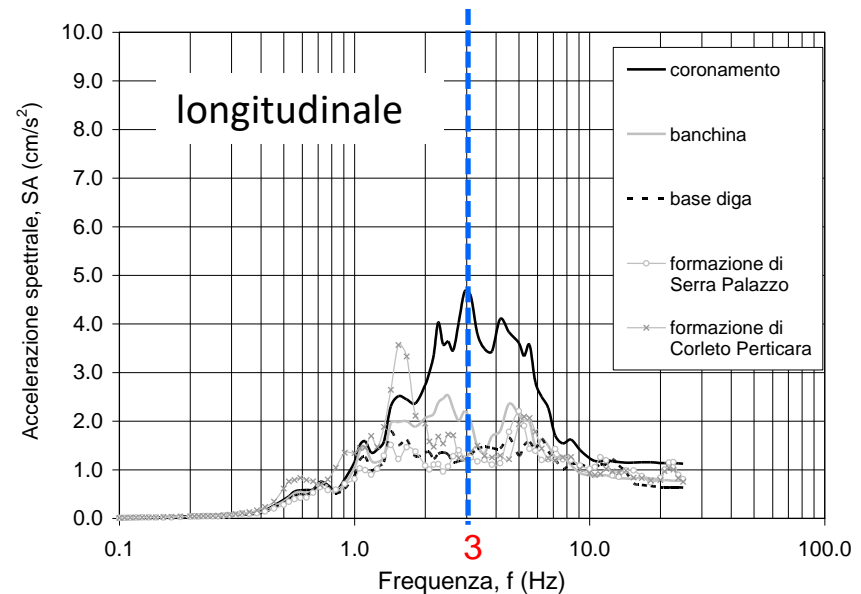
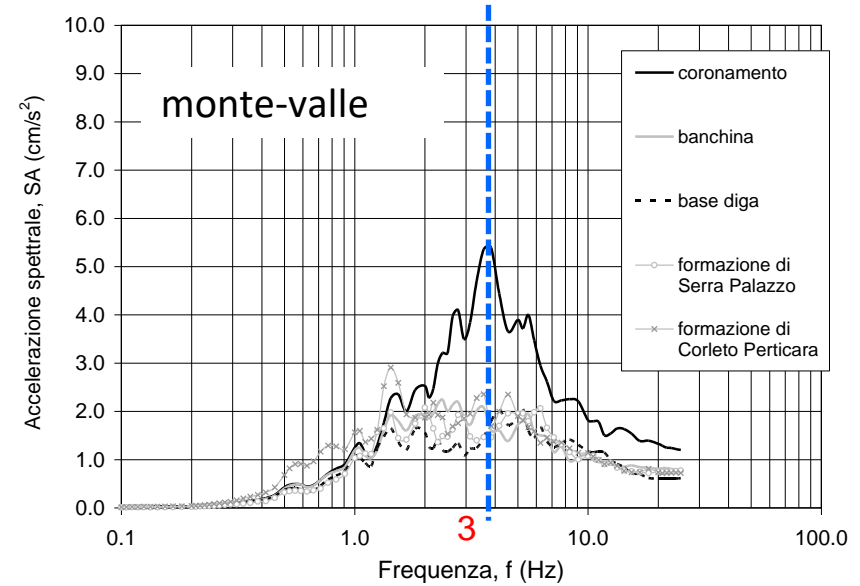
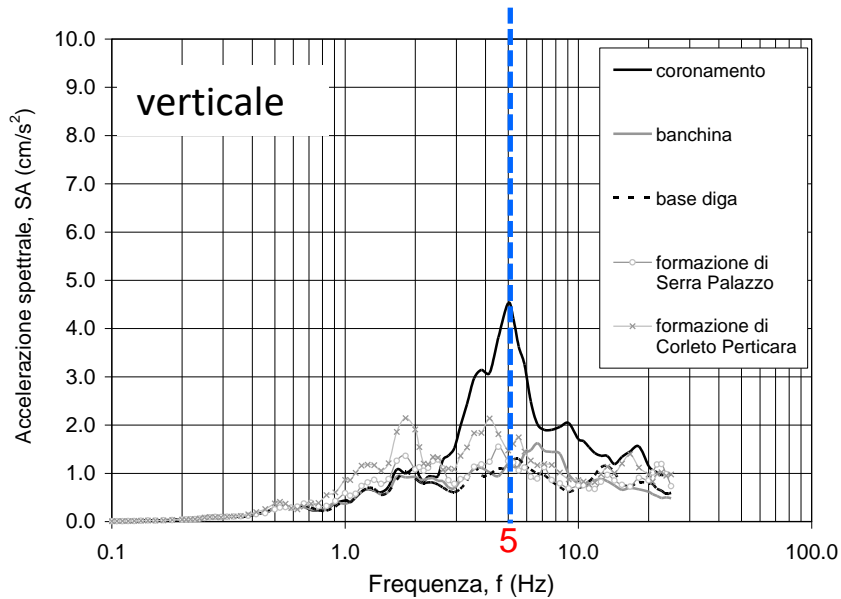
Spettri di risposta dei segnali accelerometrici registrati dalle 5 stazioni in occasione dell'evento del 26/10/2006 ( $M_w=5.8$ ;  $d=200\text{km}$ )  
(Sica et al., 2008)



# Registrazione di eventi *near-source*

## EVENTO NEAR-SOURCE

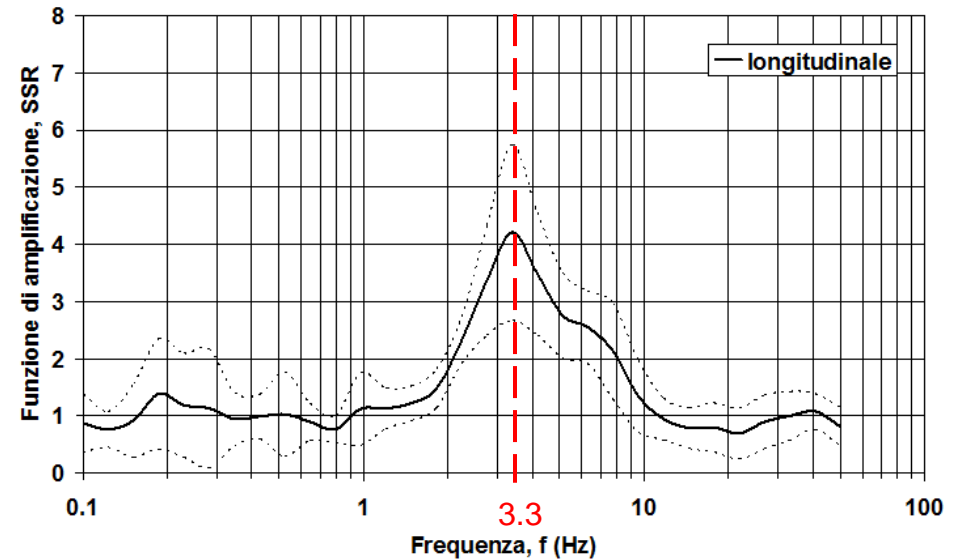
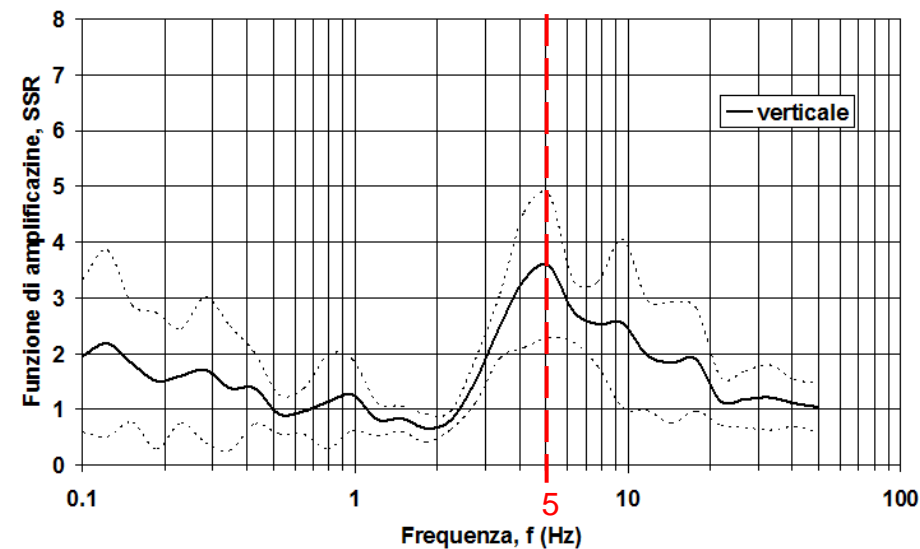
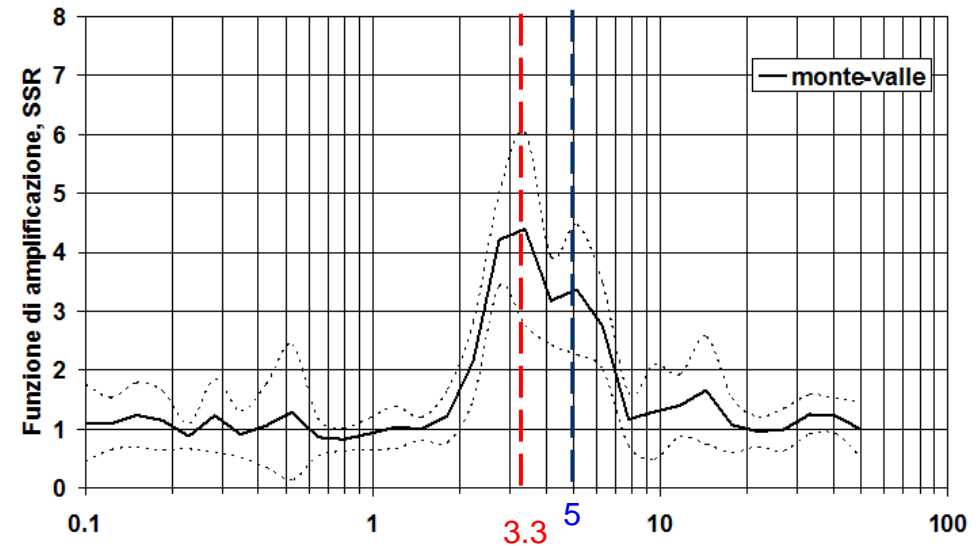
Spettri di risposta dei segnali accelerometrici registrati dalle 5 stazioni in occasione dell'evento del 03/09/2004 ( $M_w=4.0$ ;  $d=33\text{km}$ )  
(Sica et al., 2008)



(Sica, Pagano, Vinale, 2008)

# Funzioni di amplificazione con la tecnica Standard Spectral Ratio

Funzioni di amplificazione coronamento-*bedrock* di Corleto Perticara calcolate con la tecnica SSR  
(Sica et al., 2008)



## Schema di trave deformabile a taglio

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$$f_1 = \frac{v_s}{2.59H}$$

$$f_1 = 3.3\text{Hz} \quad \Rightarrow \quad v_s = 490\text{m/s} \quad \Rightarrow \quad G_0 = 480\text{MPa}$$

## Campo di variabilità di $\lambda$

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$f_1 = 1.5 \div 12$  Hz (segnali in ingresso, dir. monte-valle)

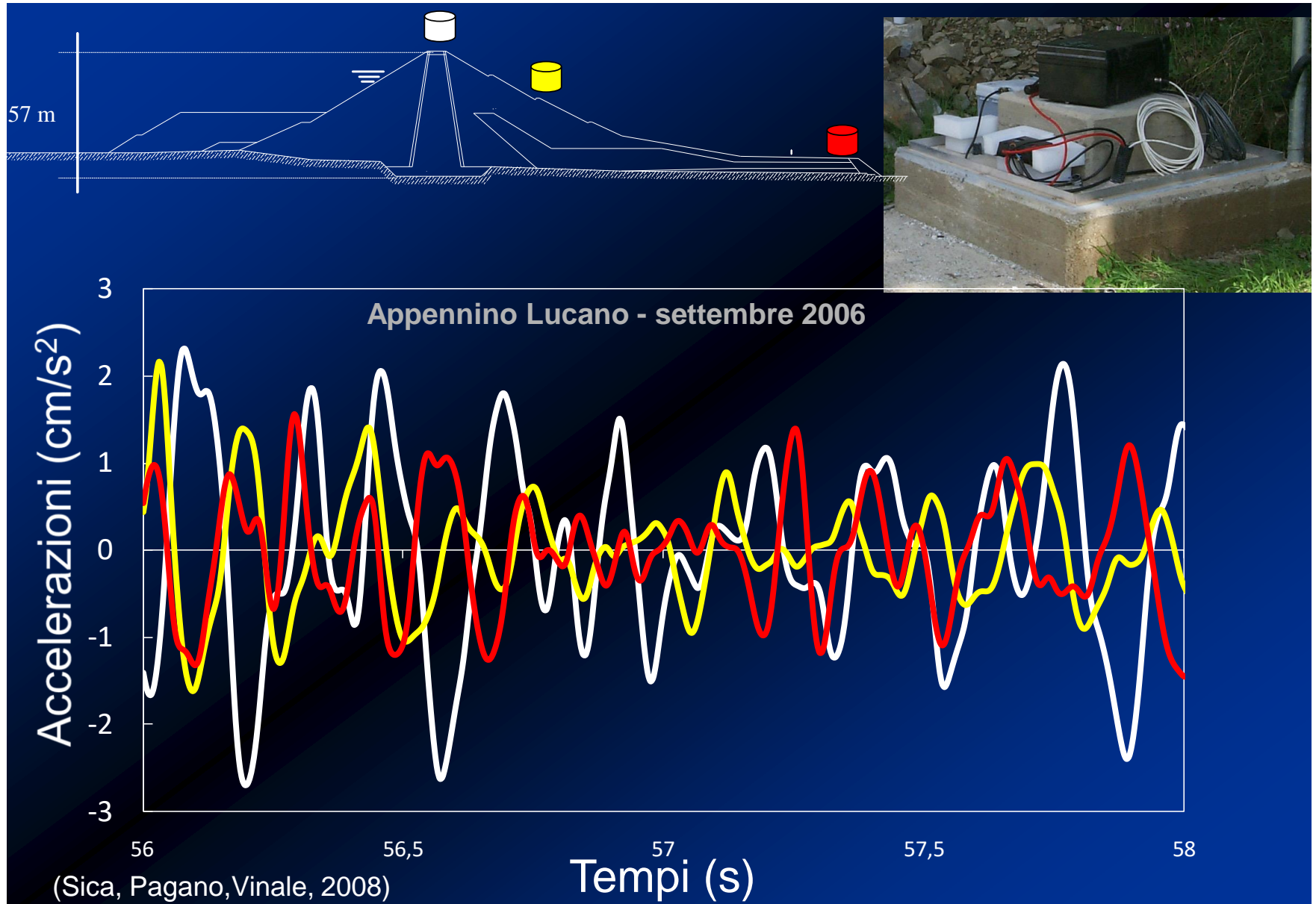
$v_s = 490$  m/s (velocità di propagazione media)



$$\lambda = 41 \div 320 \text{ m}$$

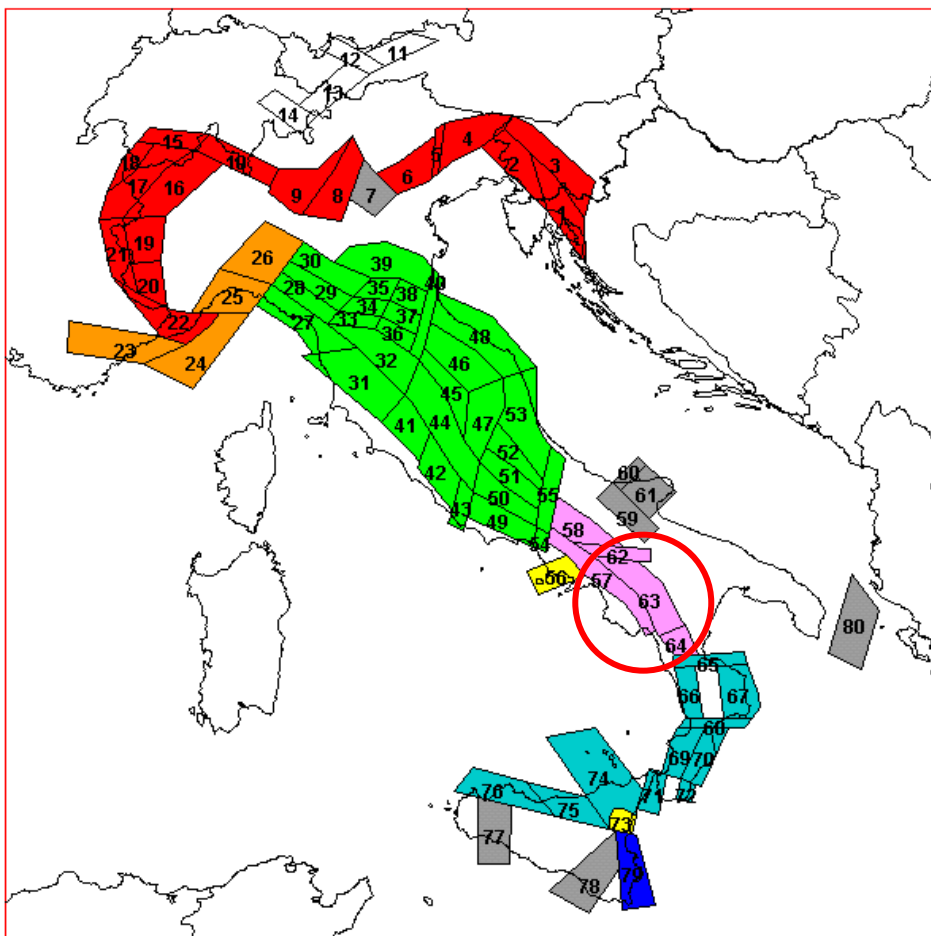
Per i valori più bassi ci si aspetta che si sviluppino moti asincroni, mentre per i valori più alti il moto tenderà ad essere pressoché sincrono

# Asincronismo del moto sismico



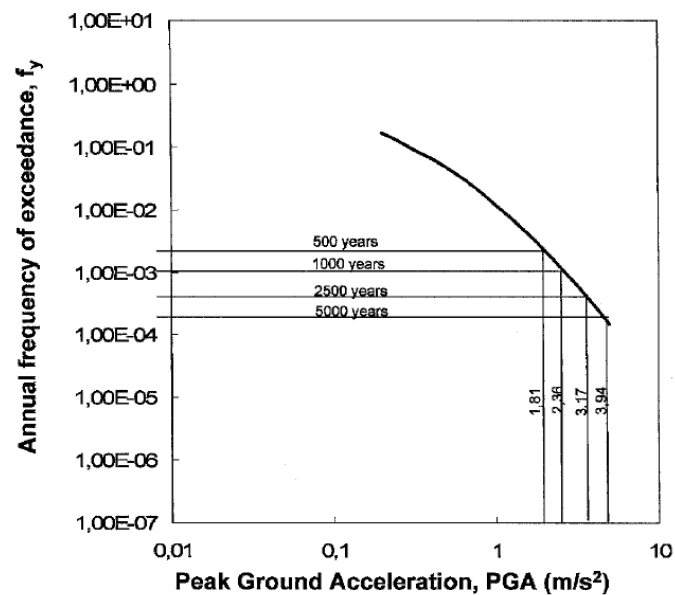
**AZIONI SISMICHE**

# Pericolosità sismica del sito



(Scandone & Stucchi, 2000)

Studio sismologico condotto  
nell'ambito del Progetto di ricerca VIA  
(Calvi, 2004)



$T_r$ (anni)	$M$	$d$ (km)	$PGA$ (m/s <sup>2</sup> )
500	5.8	8.5	1.81
1000	6.1	8.5	2.36
2500	6.4	8.5	3.17
5000	6.7	8.5	3.94

M = Magnitudo; d = distanza; PGA = accelerazione di picco al suolo

(Sica & Pagano, 2009)

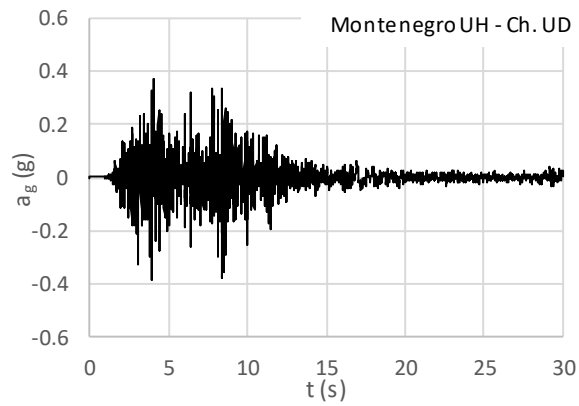
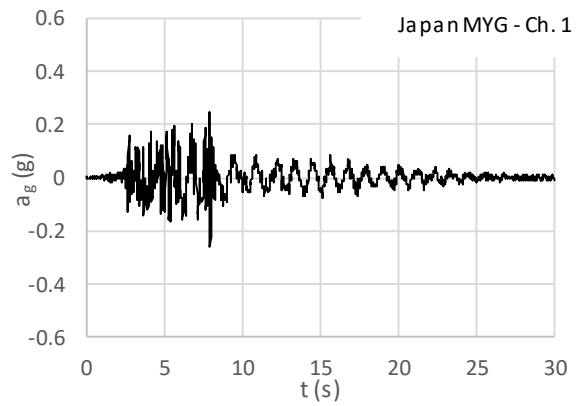
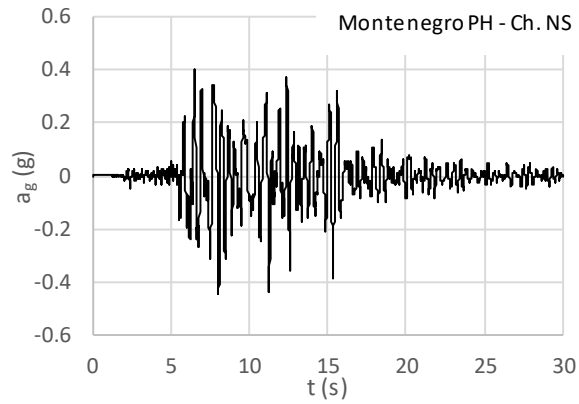
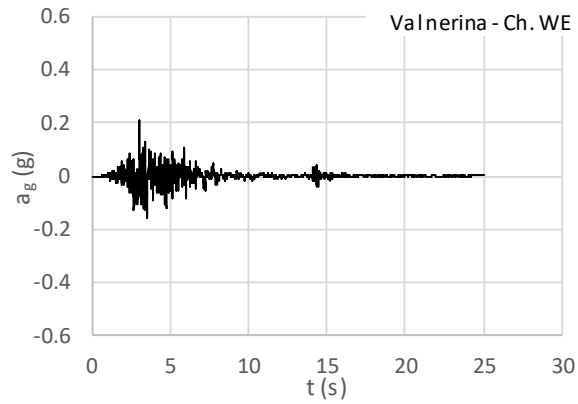
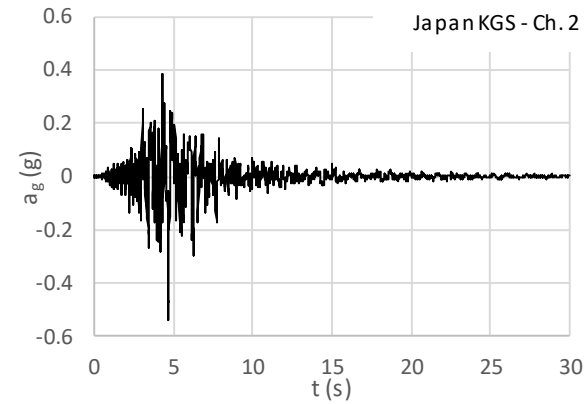
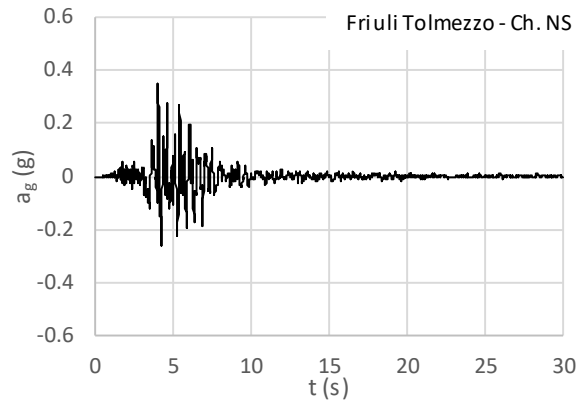
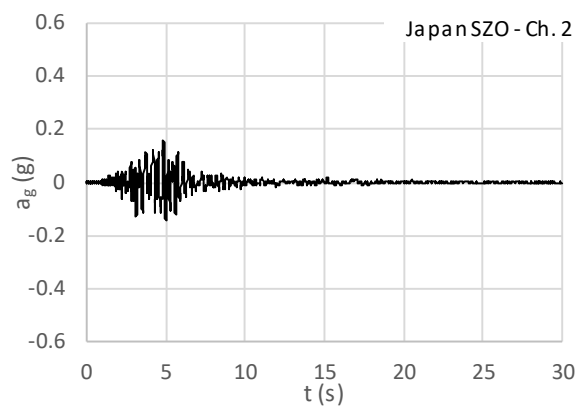


# Accelerogrammi selezionati

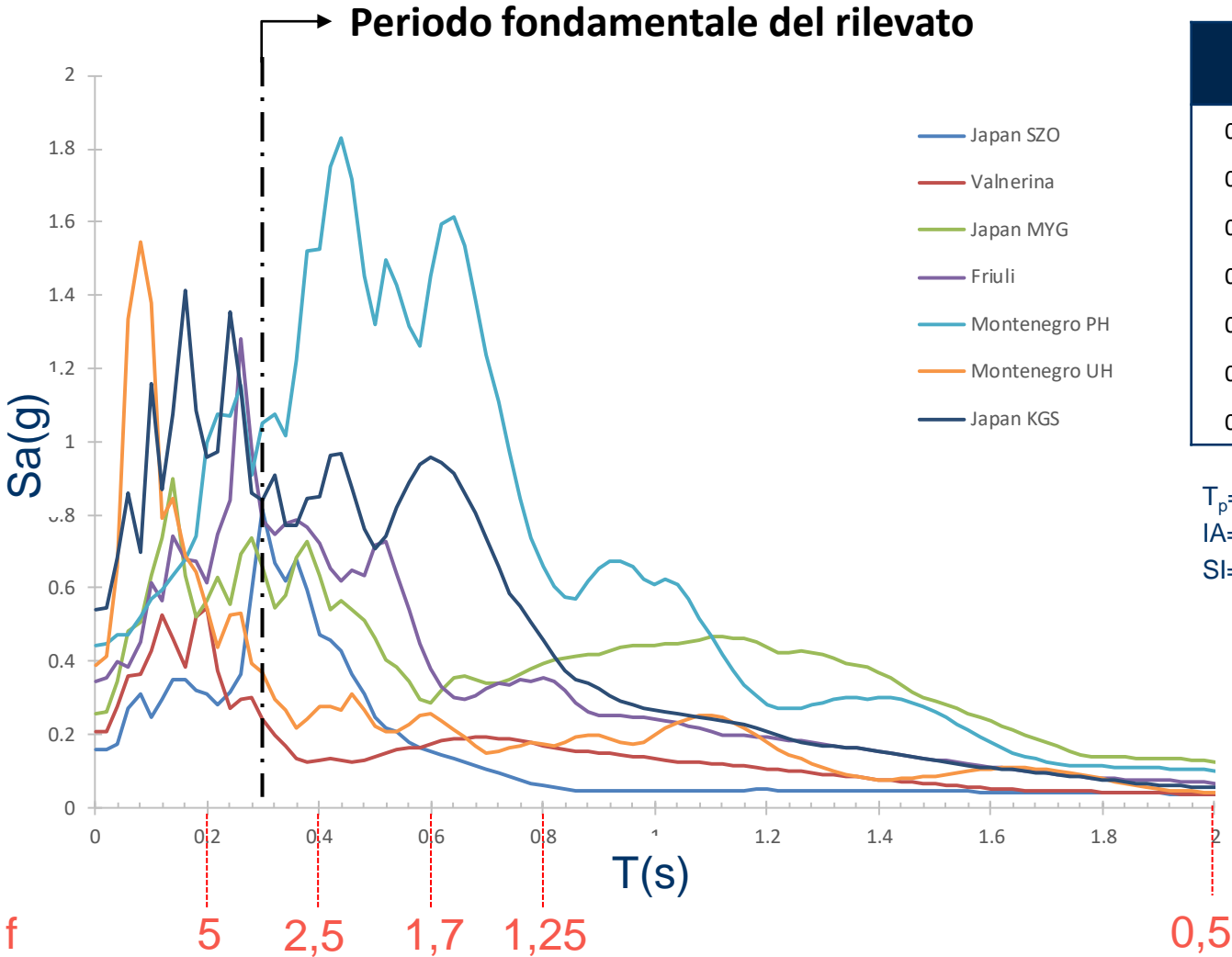
Tr (anni)	Evento	Data	M <sub>w</sub>	d (km)	Stazione	Canale	PGA (m/s <sup>2</sup> )	IA (m/s)	T <sub>p</sub> (s)	f <sub>p</sub> (Hz)	t <sub>strong</sub> (s)
500	Japan SZO	04/03/1997	5.7	6	Itoh (SZO002)	2	1.62	0.27	0.30	3.33	3.71
800	Valnerina	19/09/1979	5.8	4	Cascia	WE	2.01	0.20	0.20	5.00	3.96
1000	Japan MYG	26/07/2003	6.2	10	Ishinomaki (MYG010)	1	2.50	1.00	0.14	7.14	15.46
2500	Friuli Tolmezzo	06/05/1976	6.5	5	Tolmezzo	NS	3.50	0.78	0.26	3.85	7.47
>5000	Montenegro PH	15/04/1979	7.0	4	Petrovac- Hotel Oliva	NS	4.45	4.40	0.44	2.27	17.77
>5000	Montenegro UH	15/04/1979	7.0	4	Ulcinj-Hotel Olimpic	UD	4.49	2.47	0.06	16.67	15.95
>5000	Japan KGS	26/03/1997	6.3	13	Miyanojoh (KGS005)	2	4.93	1.37	0.24	4.17	6.65

M<sub>w</sub> = Magnitudo; d = distanza; PGA = accelerazione di picco al suolo; IA = Intensità di Arias; T<sub>p</sub> = periodo dominante;  
f<sub>p</sub> = frequenza dominante, t<sub>strong</sub> = durata di Trifunac

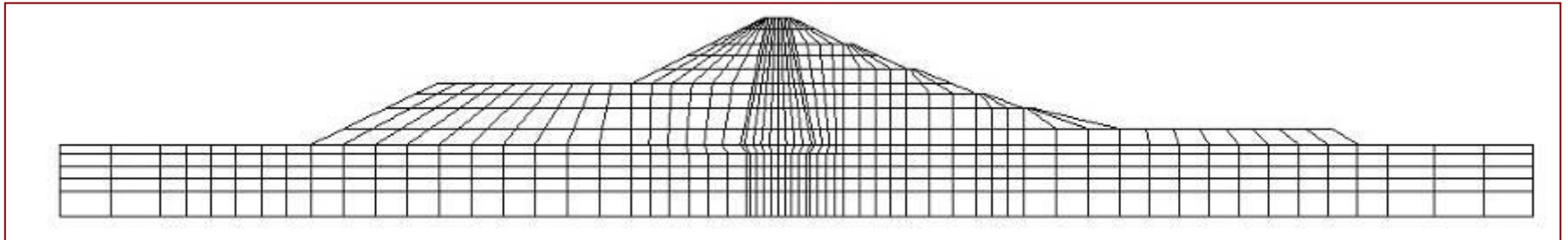
# Accelerogrammi selezionati



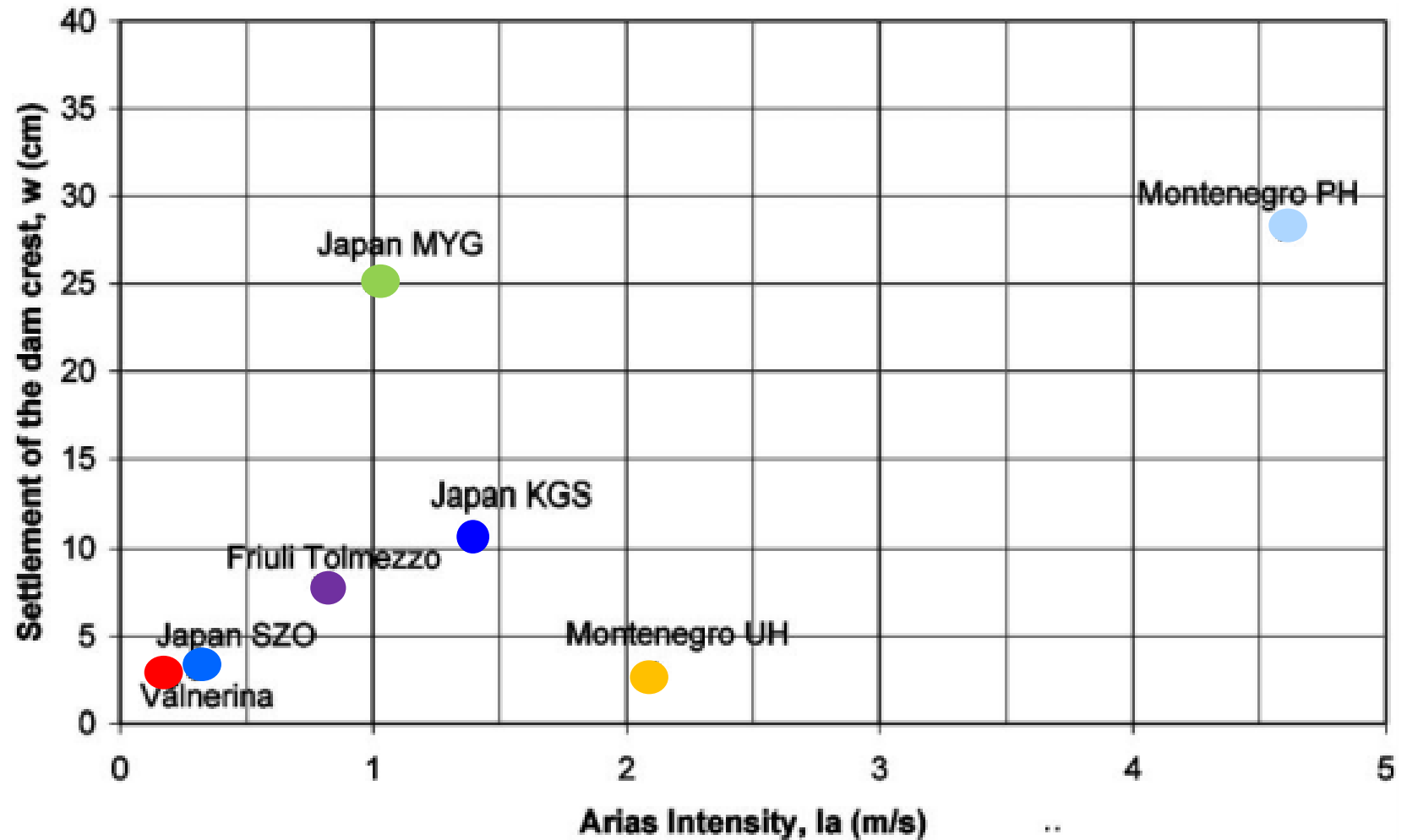
# Spettri di risposta dei accelerogrammi selezionati



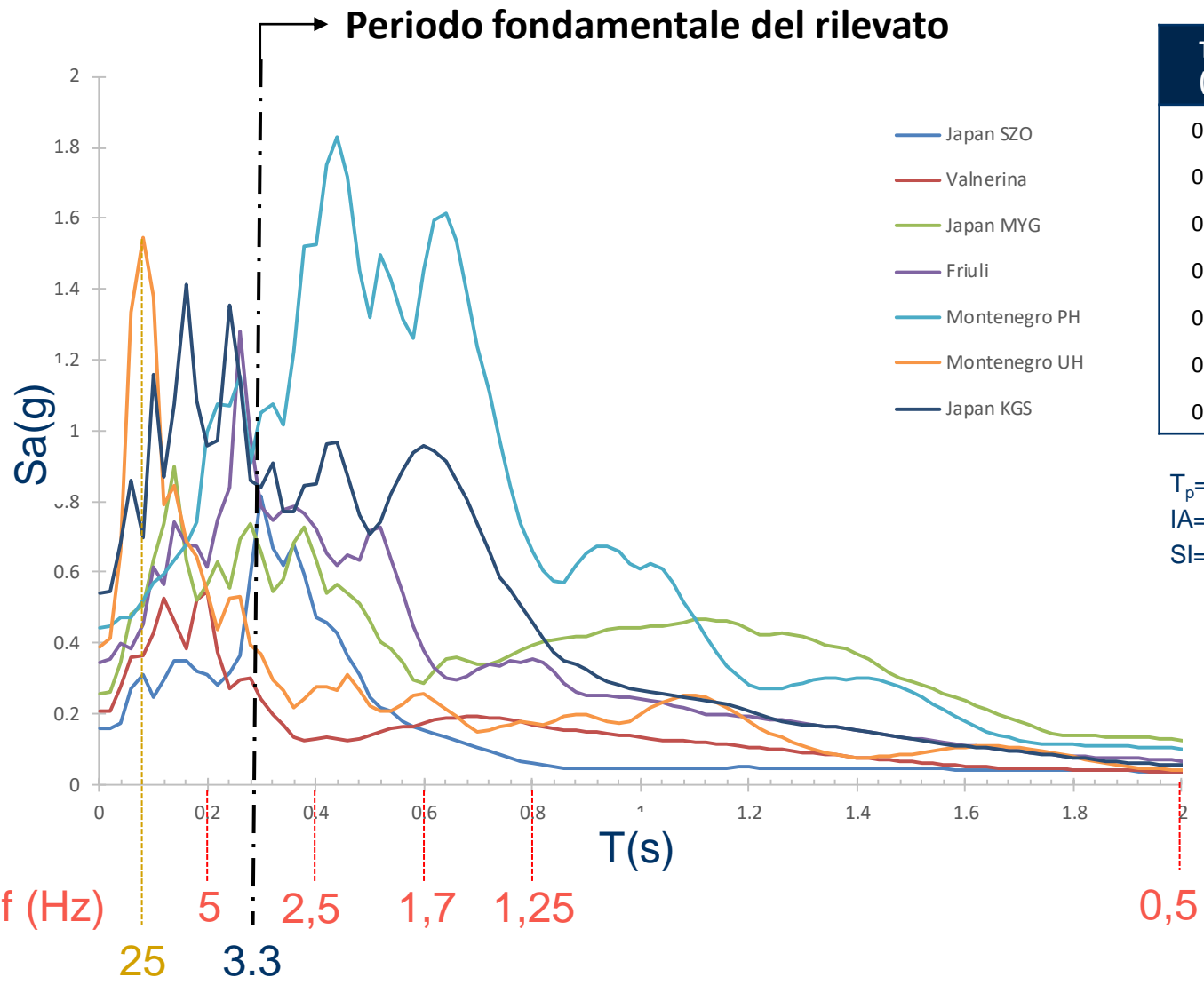
## RISULTATI DELLE ANALISI



# Cedimenti permanenti del coronamento



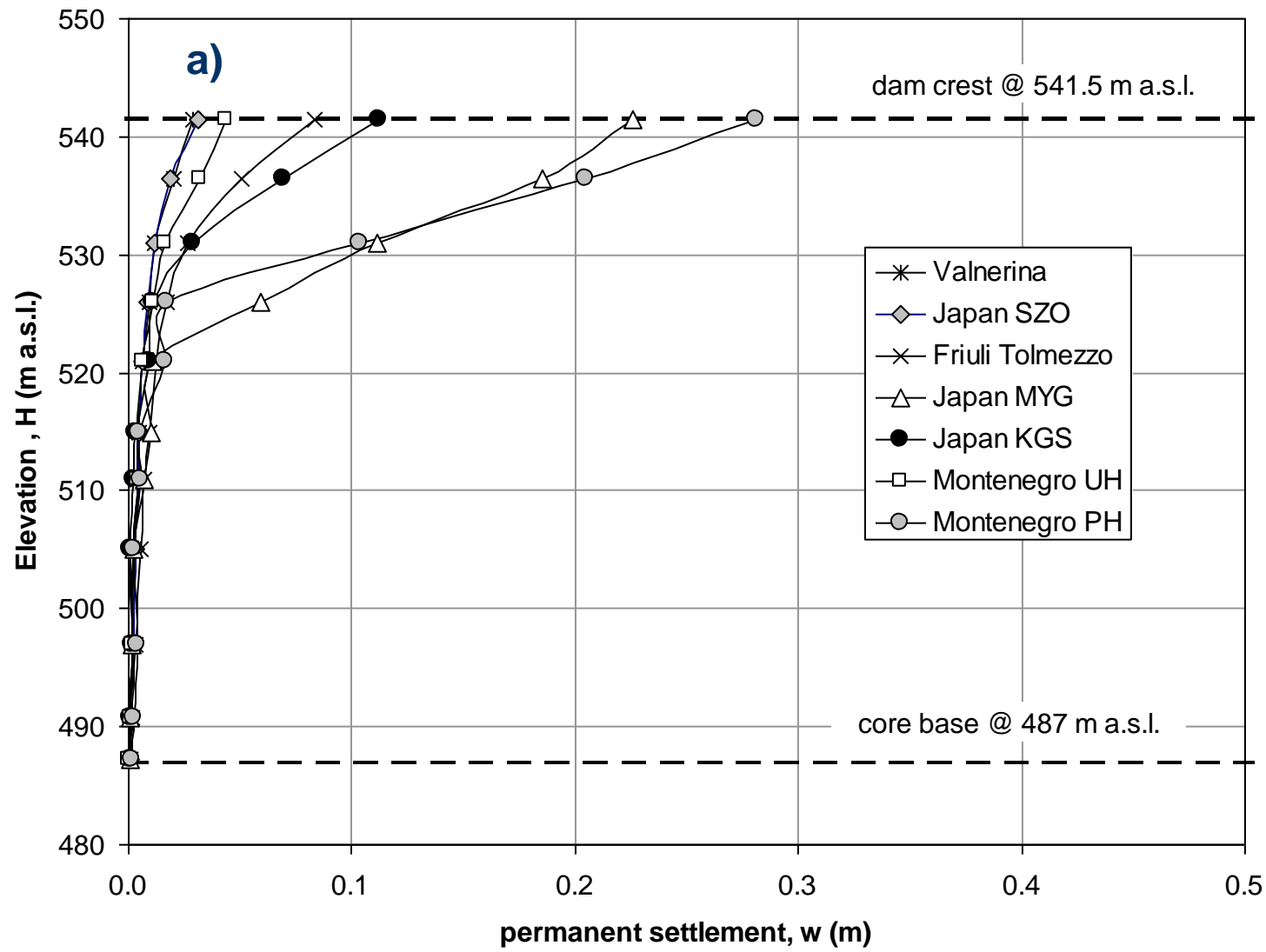
# Spettri di risposta dei accelerogrammi selezionati



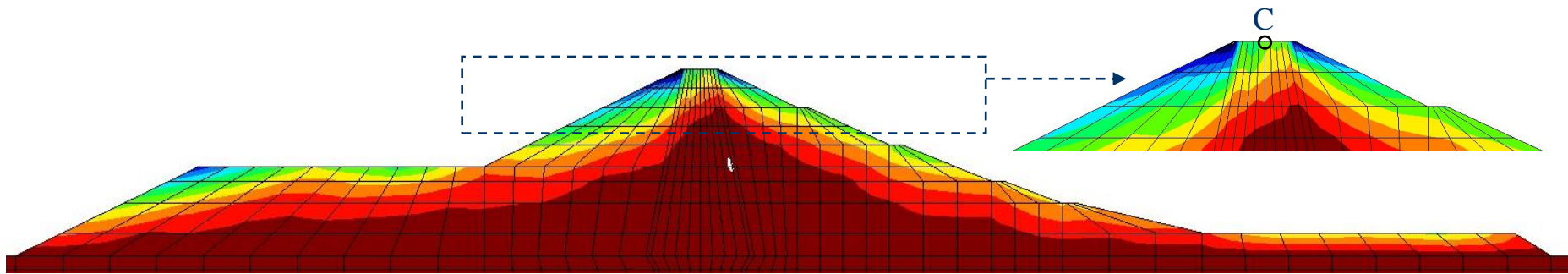
$T_p$ (s)	IA (m/s)	$t_{strong}$ (s)
0.30	0.27	3.71
0.20	0.20	3.96
0.14	1.00	15.46
0.26	0.78	7.47
0.44	4.40	17.77
0.06	2.47	15.95
0.24	1.37	6.65

$T_p$ =periodo dominante;  
IA=Intensità di Arias;  
SI=Intensità di Housner

# Profili di cedimento permanente in asse al nucleo



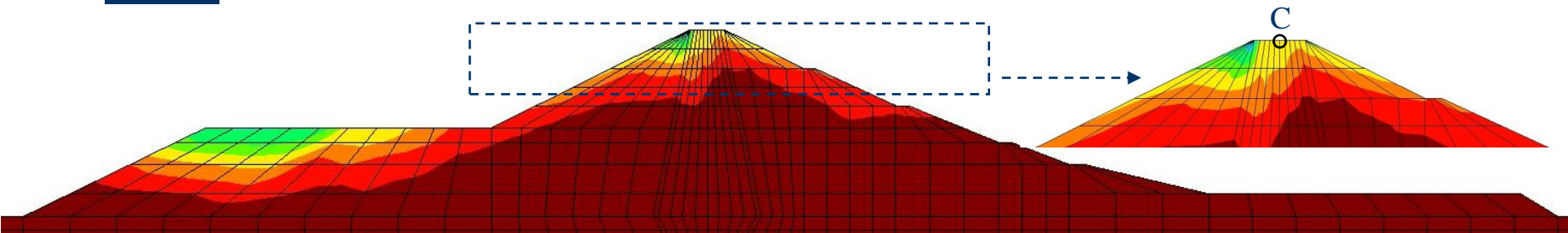
# Contorni di cedimento permanente



w (m)



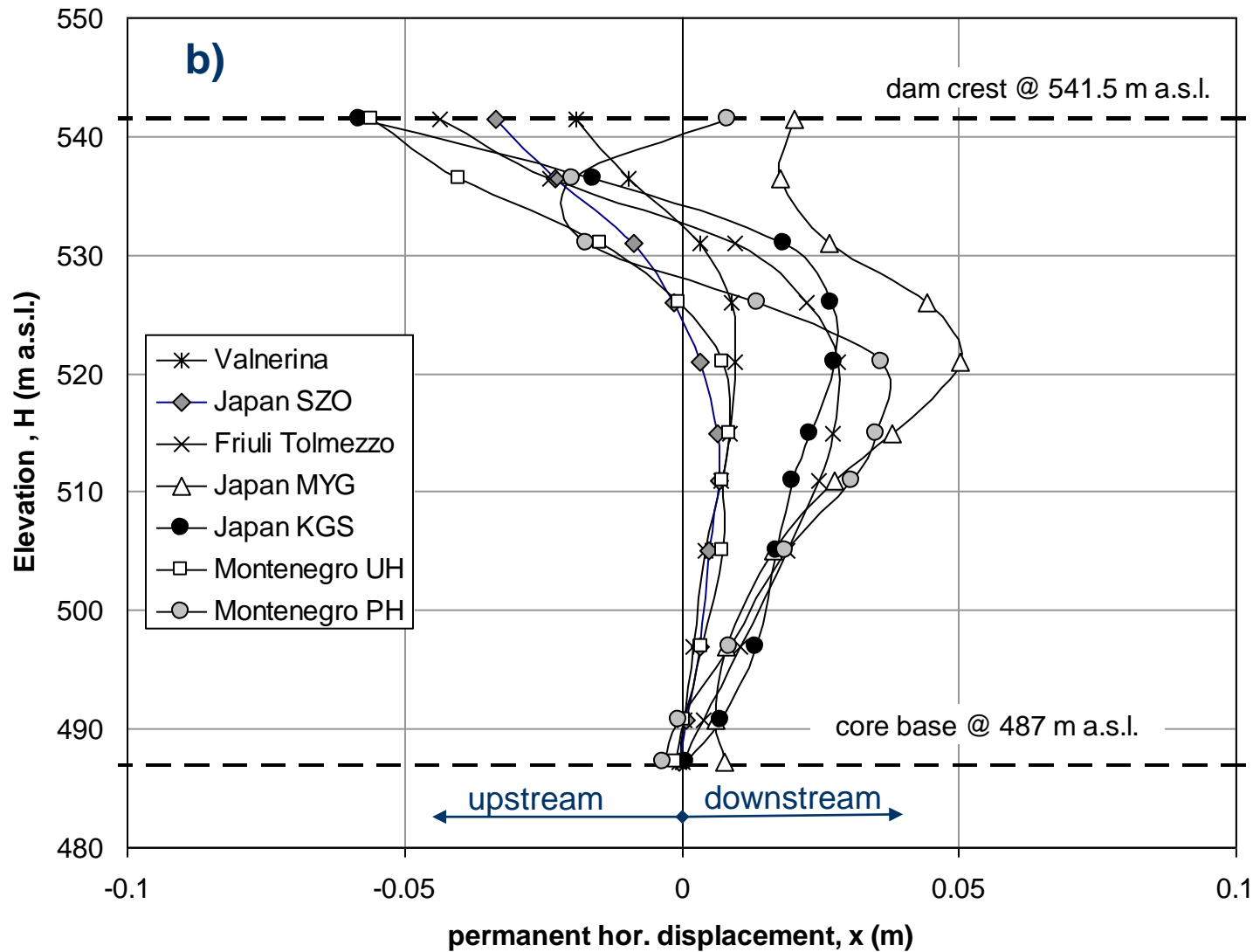
Montenegro PH



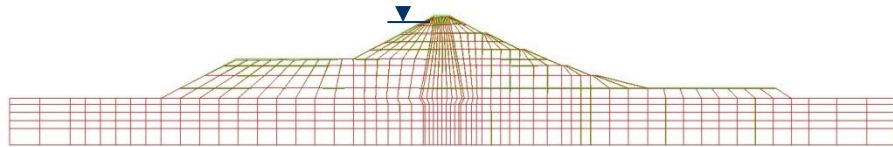
Japan MYG



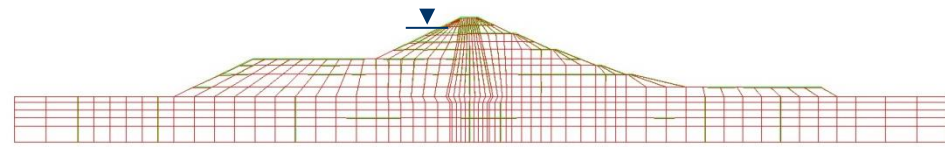
# Profili di spostamento orizzontale permanente



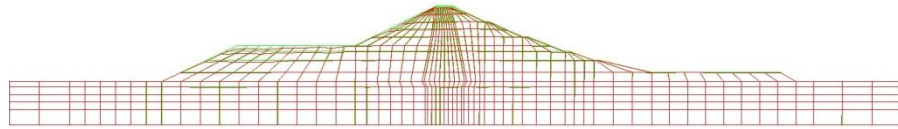
# Deformate post-sismiche



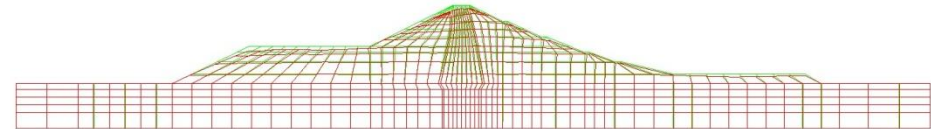
Valnerina



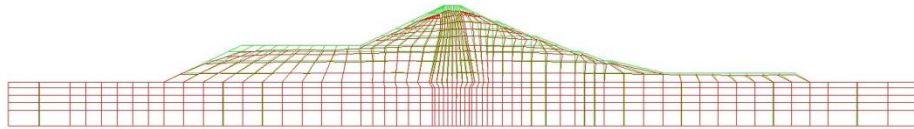
Japan SZO



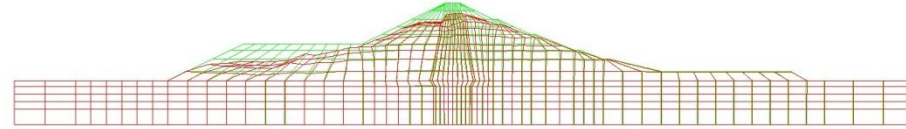
Montenegro UH



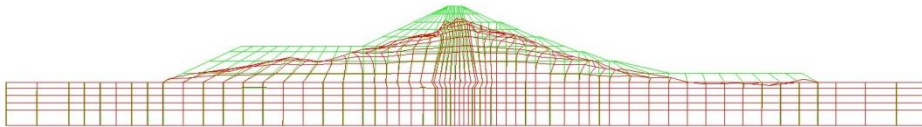
Friuli Tolmezzo



Japan KGS



Japan MYG



Montenegro PH

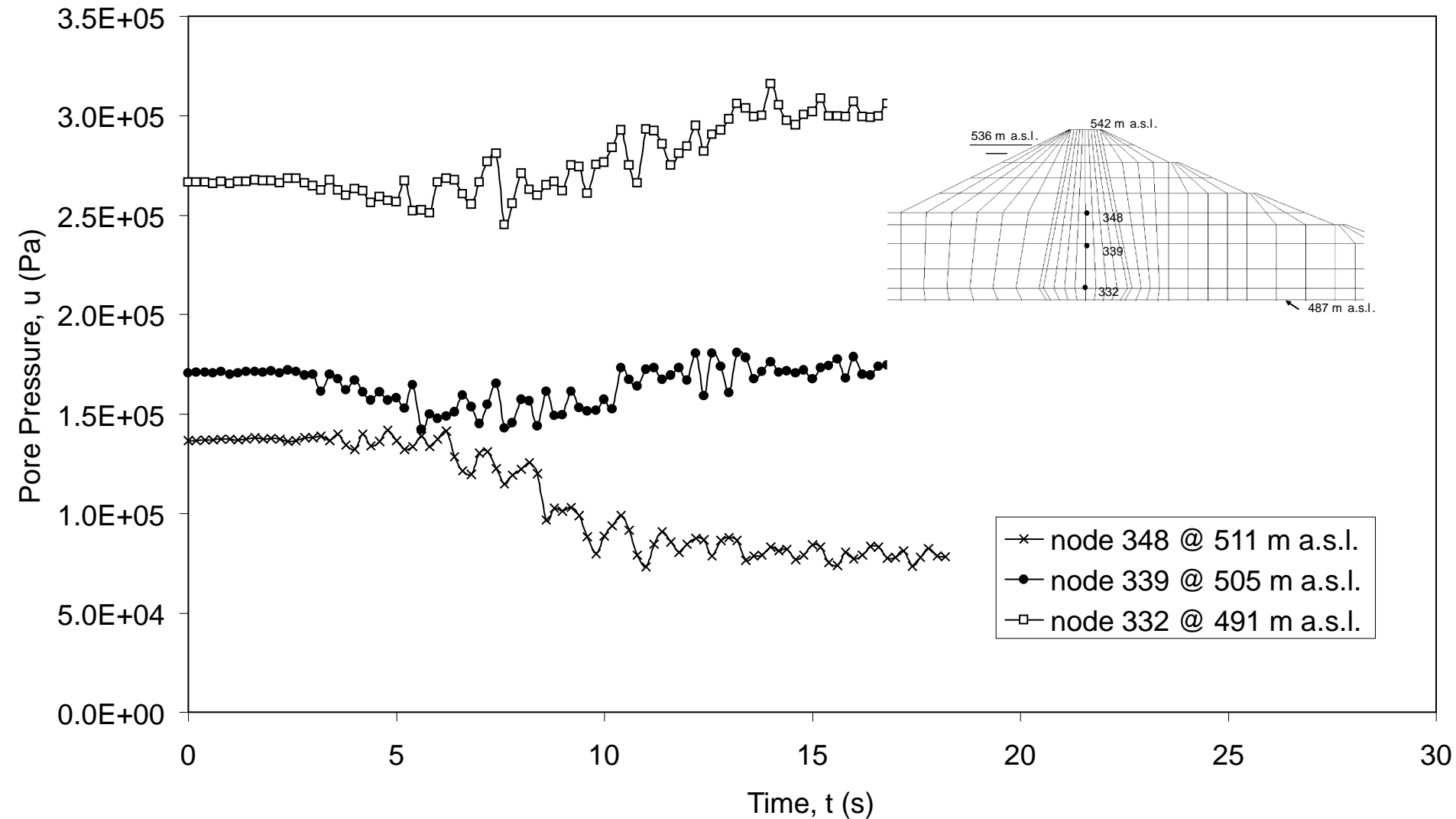
50 m



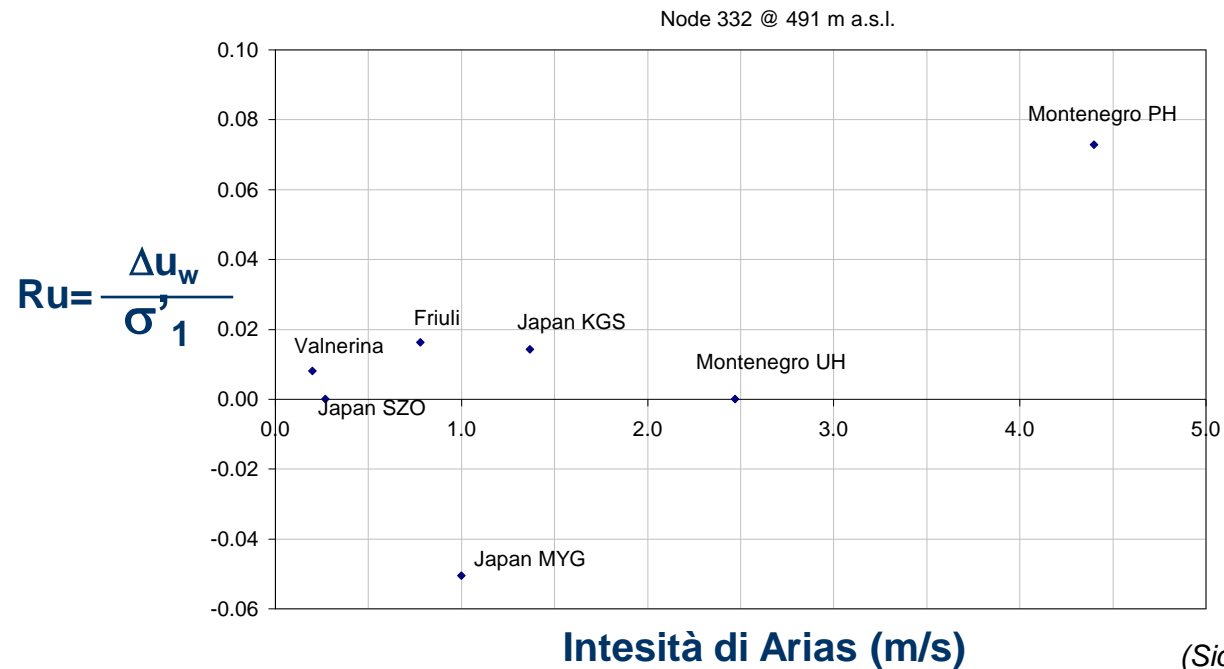
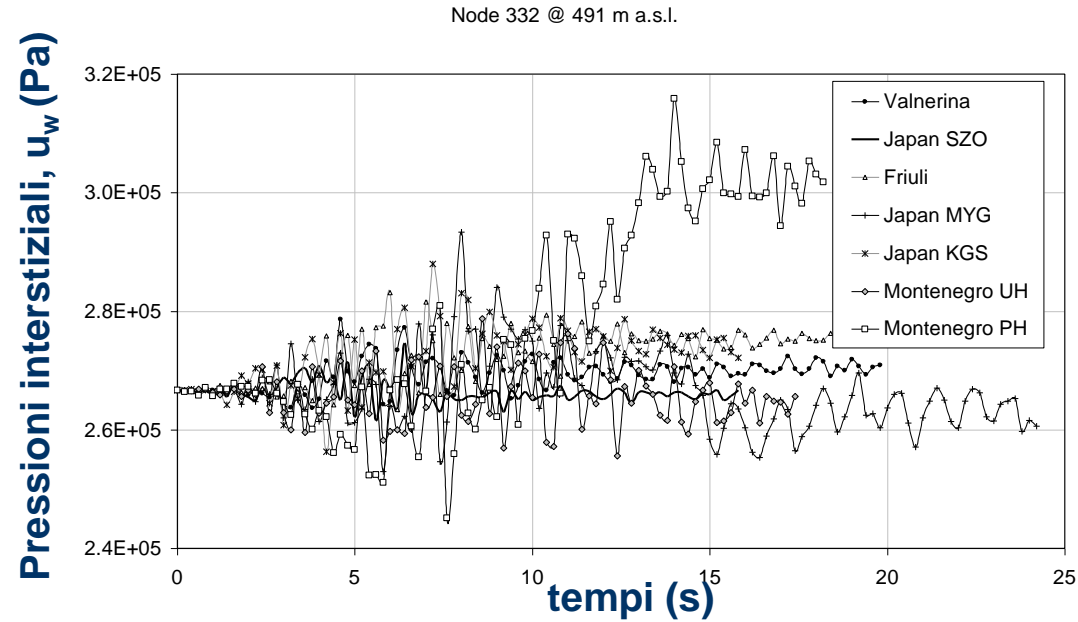
Magnitude factor for  
displacement=30

# Pressioni interstiziali sismo indotte

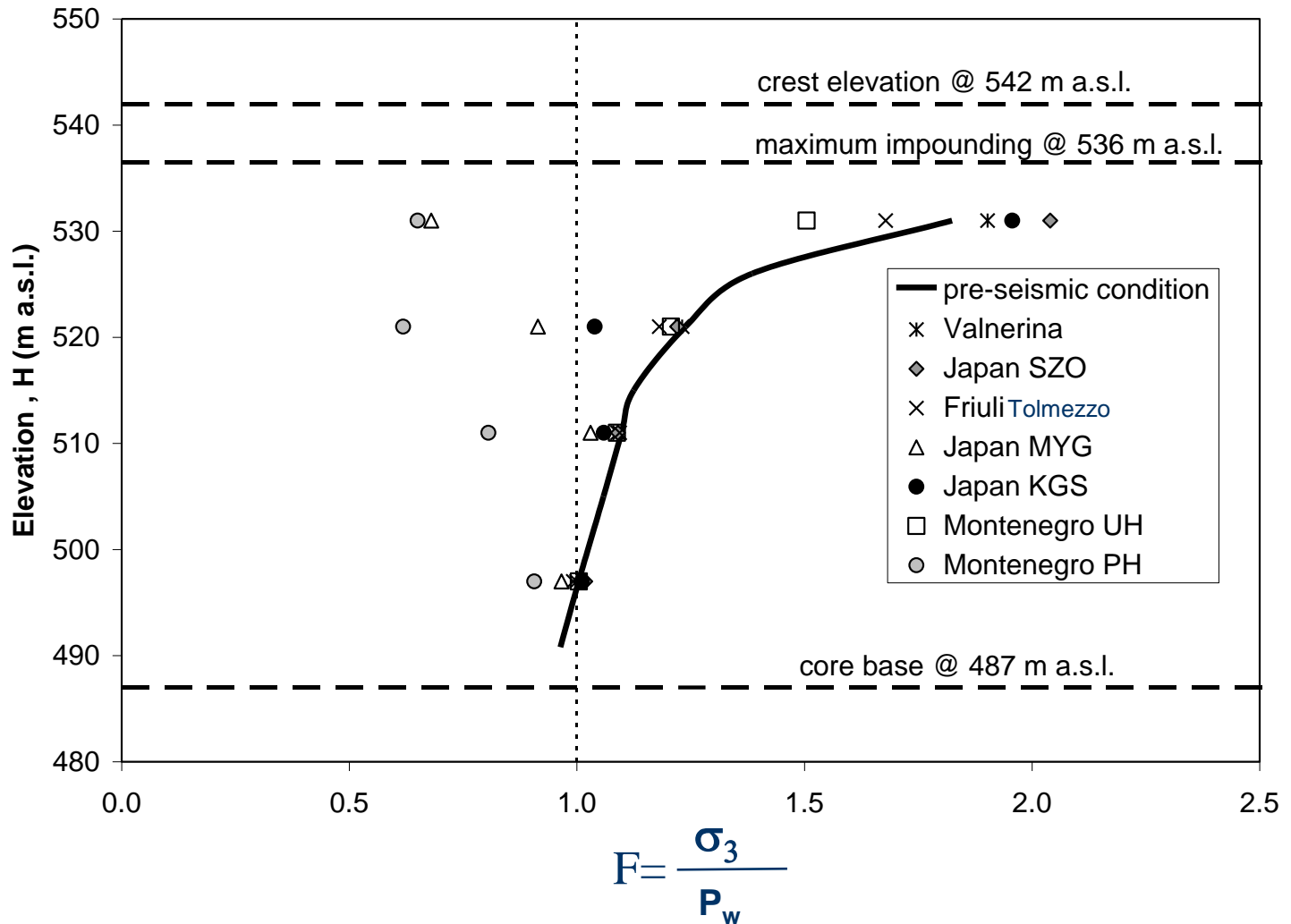
## MONTENEGRO PH



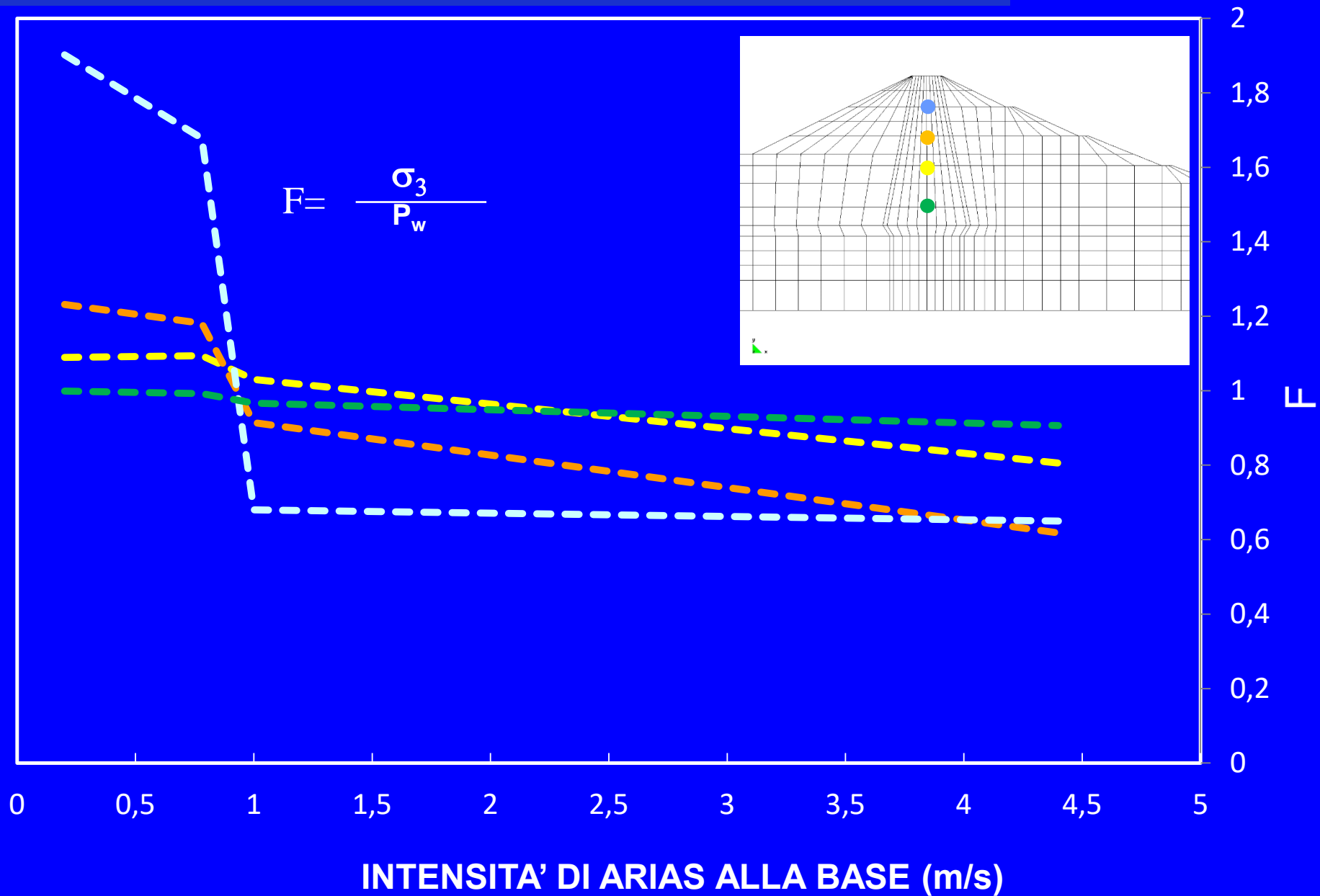
# Pressioni interstiziali sismo-indotte e coeff. di pressione interstiziale



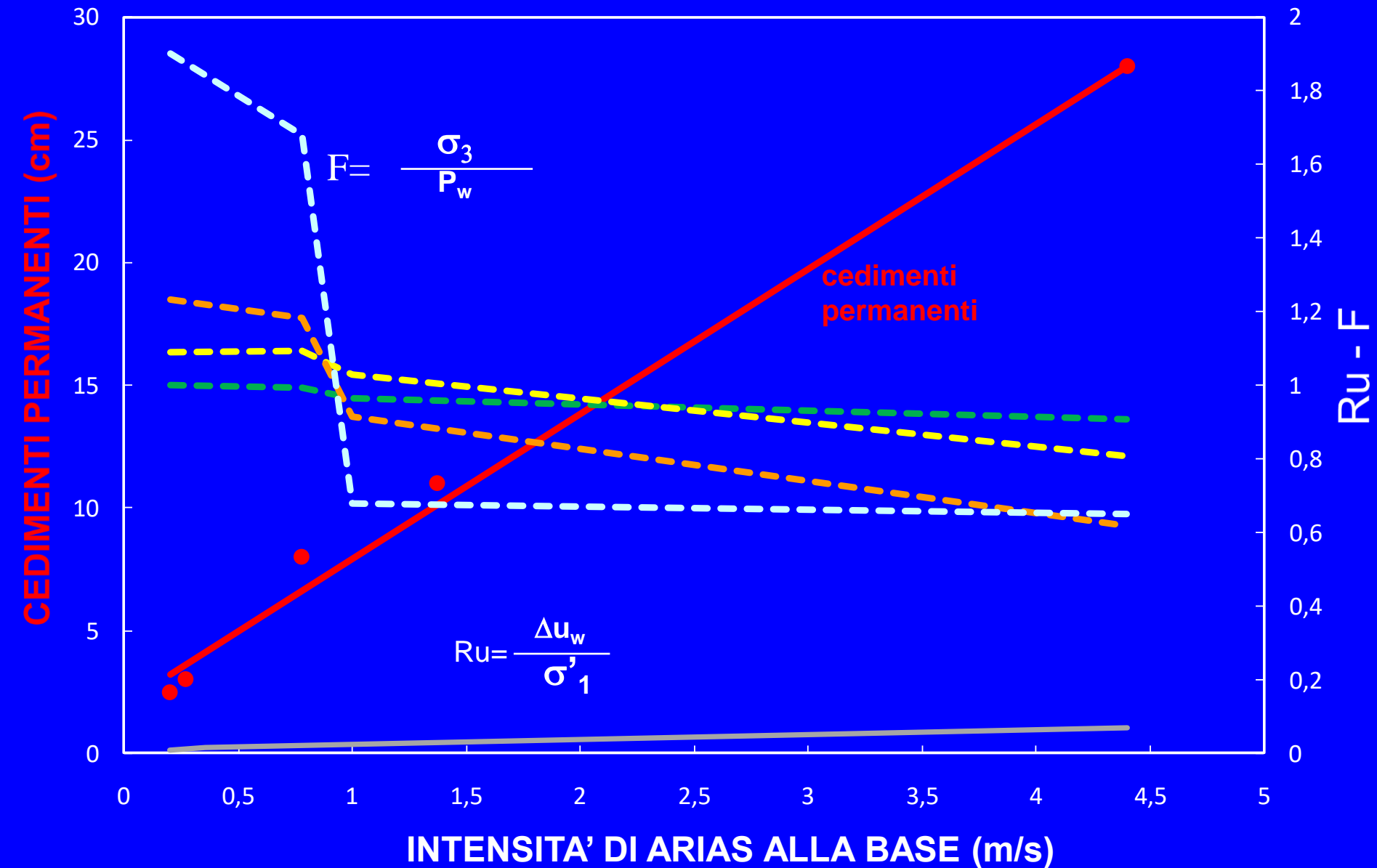
# Coefficienti di sicurezza locale alla fratturazione idraulica



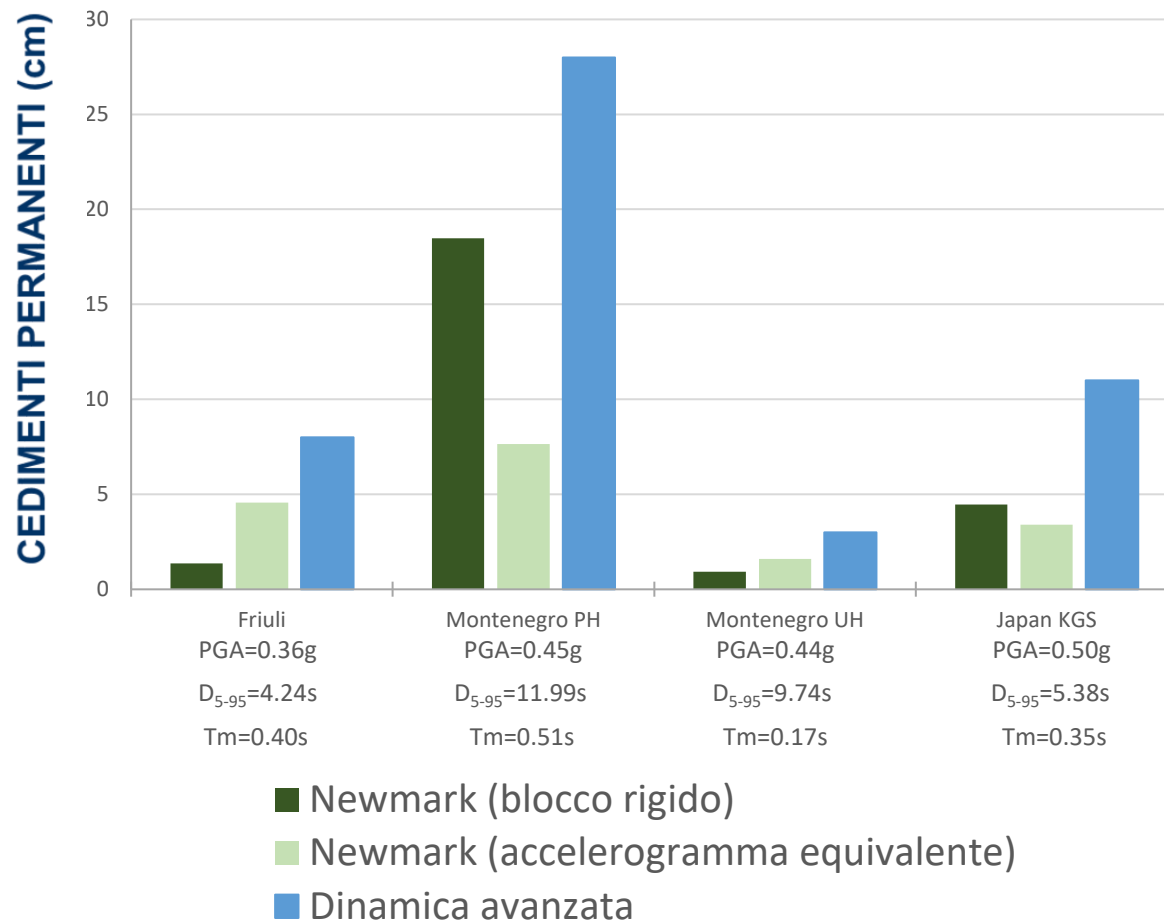
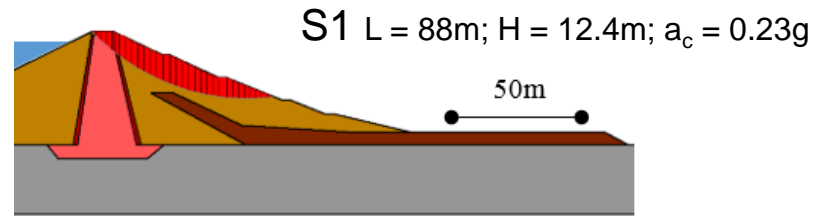
# Coefficienti di sicurezza locale alla fratturazione idraulica



# Rappresentazioni sintetiche per il controllo post-sismico



# Confronto di spostamenti permanenti calcolati con metodi diversi

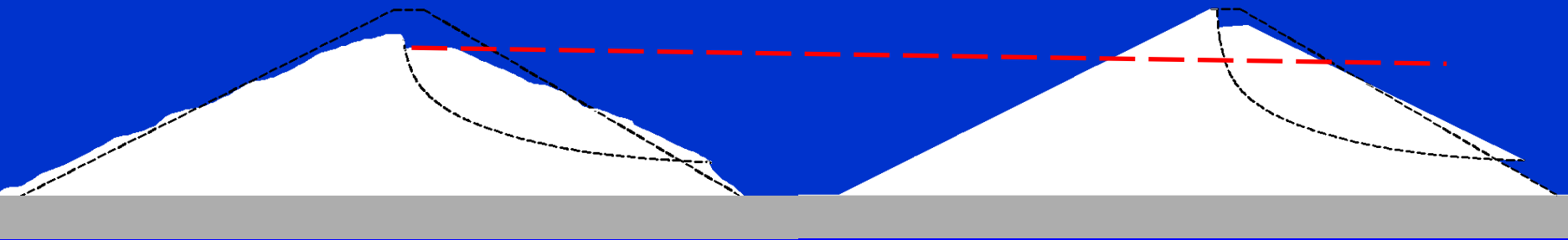




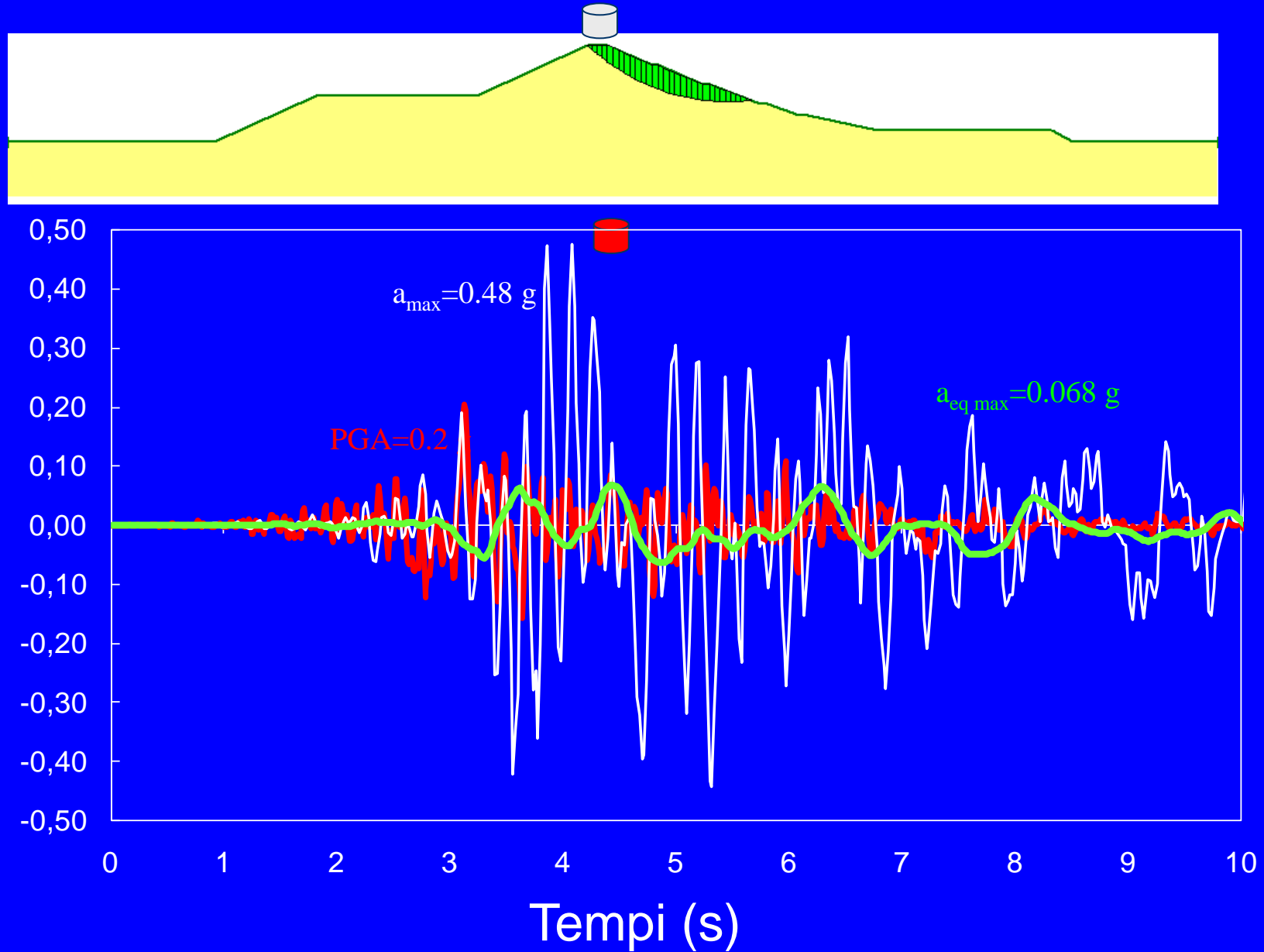
# Confronto di spostamenti calcolati con metodi diversi

**ANALISI DINAMICA COMPLETA**

**NEWMARK**



# Asincronismo della risposta sismica



## CONCLUSIONI

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- La caratterizzazione del comportamento sismico richiede valutazioni di stati tensionali, stati deformativi, e pressioni interstiziali: l'uso di strumenti previsionali complessi è inevitabile e può essere associato sinergicamente all'uso di approcci semplificati
- La caratterizzazione del comportamento sismico richiede la preliminare caratterizzazione del comportamento statico
- E' utile disporre di misure accelerometriche al sito di ubicazione della diga e disporre di abachi previsionali costruiti con eventi da scenario; le misure accelerometriche tornano utili anche per la caratterizzazione del comportamento sismico a piccole deformazioni