RECLAMATION
Managing Water in the West

Numerical simulation of seismic behavior of Menta Dam, Italy

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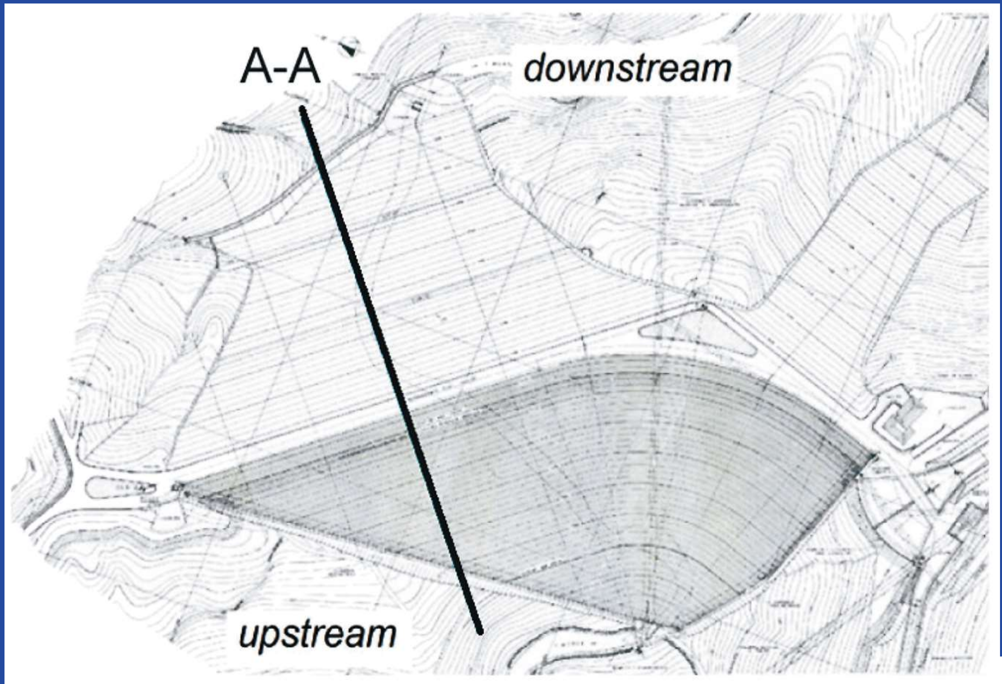


Menta Dam cross section selected for the 2019 benchmark workshop.

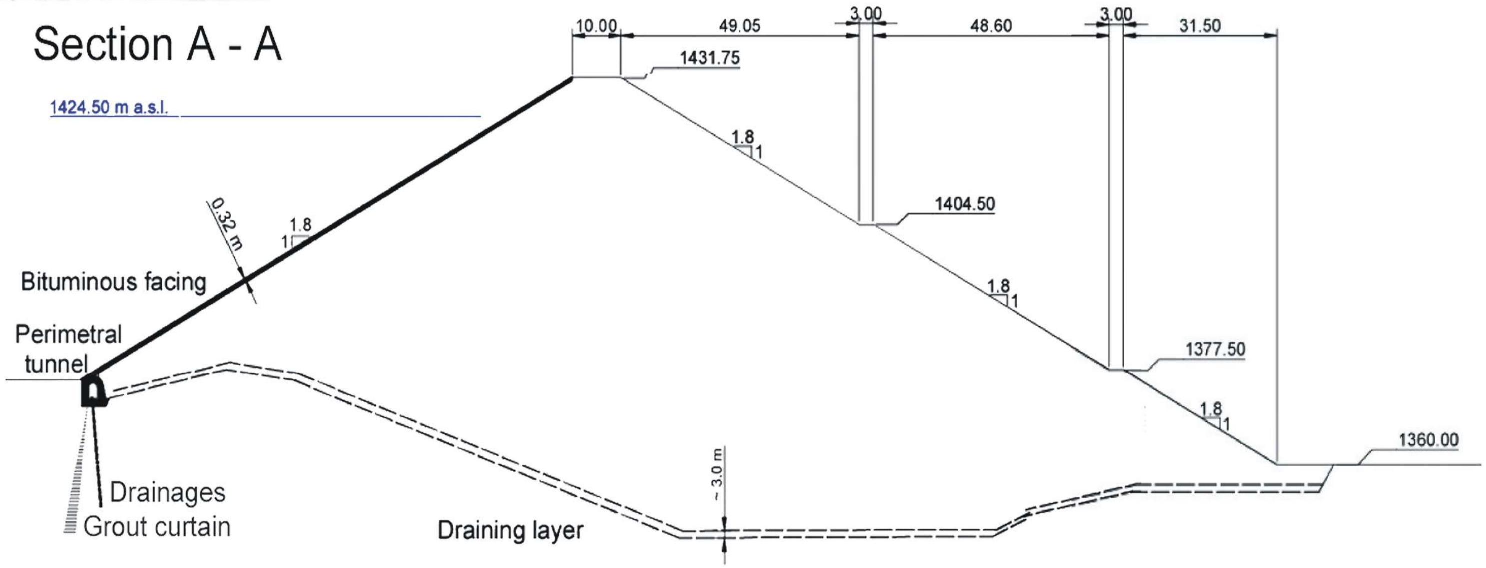


Table 1(a). Material properties used in static and seismic analyses of Menta Dam.

Item name, group name	**Unit weight, γ (kN/m^3)**	**Young's modulus, E (kPa)**	**Poisson ratio, ν**	**Permeability, k (m/sec)**	**Angle of internal friction, φ (°)**	**Porosity**	**Reference #**
Foundation, fdn	27	$E_{rock} = 7 \times 10^6$ in Eqns. (1, 2)	0.25	1×10^{-7}	-	0.10	[1,10]
Grout curtain, ctn	21	1.4×10^4	0.21	0	-	0.01	[3]
Concrete tunnel, tun	24	3.2×10^7	0.16	1×10^{-9}	-	0.01	
Drainage layer, drn	20	$E_{rock} = 7 \times 10^6$ in Eqns. (1)	0.25	1×10^{-3}	-	0.30	

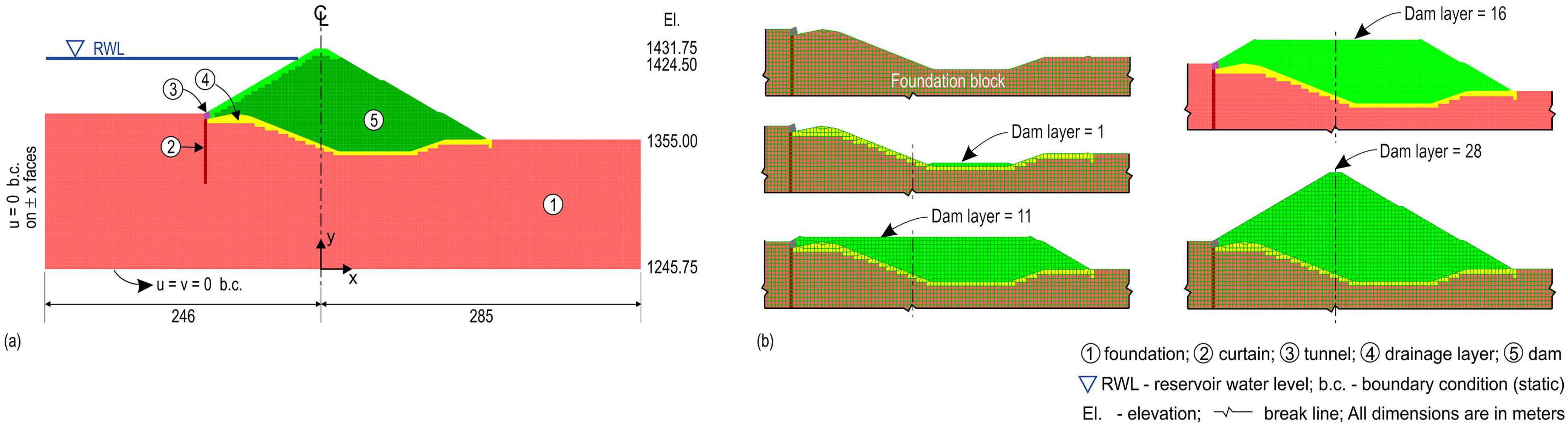
Rockfill, dam	23	$25164 \times (p')^{0.6686}$	0.20	2×10^{-5}	$\phi'_{crit} = 36.45$; $m = 3$; $Q = 10$; $D_r = 0.9$ in Eqn. (3)	0.30	[2,7,10]
Bituminous facing, fac	24	1.5×10^5	0.44	0	-	0.03	[5,10]

- not used; p' = mean principal effective stress in kPa; $\underline{z}$ in Eqn. (2) is depth measured from top of the Foundation where $\underline{z}$=0 and increases in the negative y-coordinate direction, see Fig. 4(a).

$$E_{rock\text{-}mass} = E_{rock} \times 10^{0.0186 \times RQD - 1.91} \quad (1)$$

$$RQD = 17.536 \times \ln(\underline{z}) + 24.847 \quad (2)$$

$$\phi' = \phi'_{crit} + m \times [D_r \times (Q - \ln(p')) - 1] \quad (3)$$



Numerical model of Menta Dam cross section under study:

(a) model details;

(b) illustration of staged construction modeled.

Table 1(b). Modulus and damping factors used in seismic analyses.

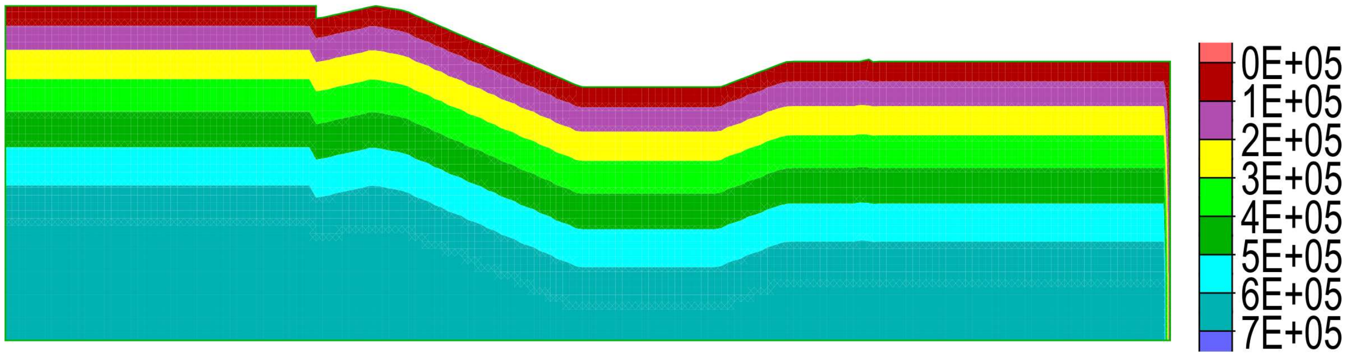
Cyclic shear strain, γ_c(%)	1×10^{-4}	3×10^{-4}	1×10^{-3}	3×10^{-3}	1×10^{-2}	3×10^{-2}	1×10^{-1}	3×10^{-1}	1	Reference #
Shear modulus reduction factor, G/G_{max}	1.0	0.95	0.88	0.76	0.56	0.36	0.20	0.11	0.04	[1]
Damping ratio, D (%)	0.7	1.2	3.0	5.5	11.0	15.0	19.0	21.0	22.5	
Rayleigh Damping, (%)	0.05									
Implementation in FLAC	3-parameter sigmoidal function, M_s, with parameters a = 1.03, b = - 0.65, x_0 = - 1.9 in Eqn. (4). For Rayleigh damping, the specified damping is percent of critical damping, and central frequency is 1.2 Hz.									

$$M_S = a / (1 + e^{expo});\ expo = -((L - x_0) / b);\ L = \log(\gamma_c) \tag{4}$$

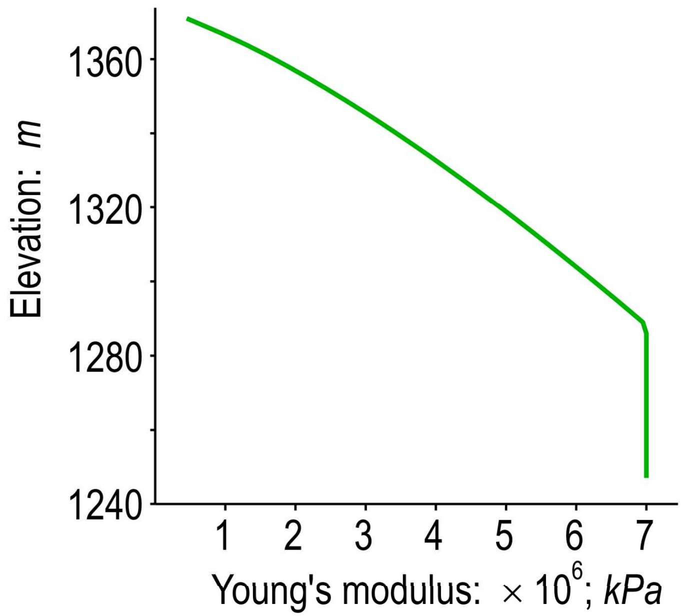
$$\text{Shear modulus, } G = E / 2(1 + \nu) \tag{5}$$

$$\text{Bulk modulus, } K = E / 3(1 - 2\nu) \tag{6}$$

$$\text{Shear wave velocity, } V_S = (G / \rho)^{1/2};\ \rho = \gamma / g \tag{7}$$

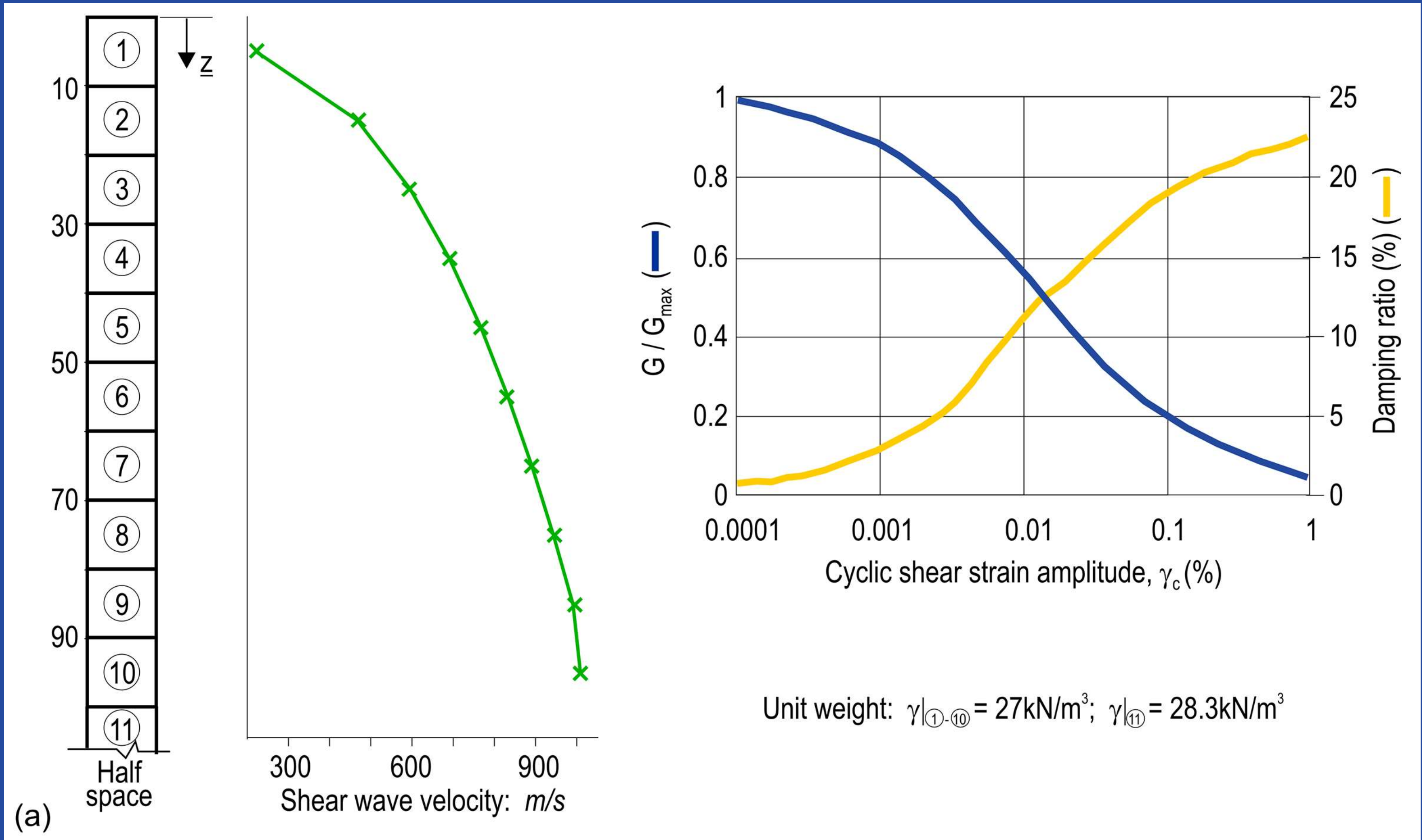


(a) Contour plot

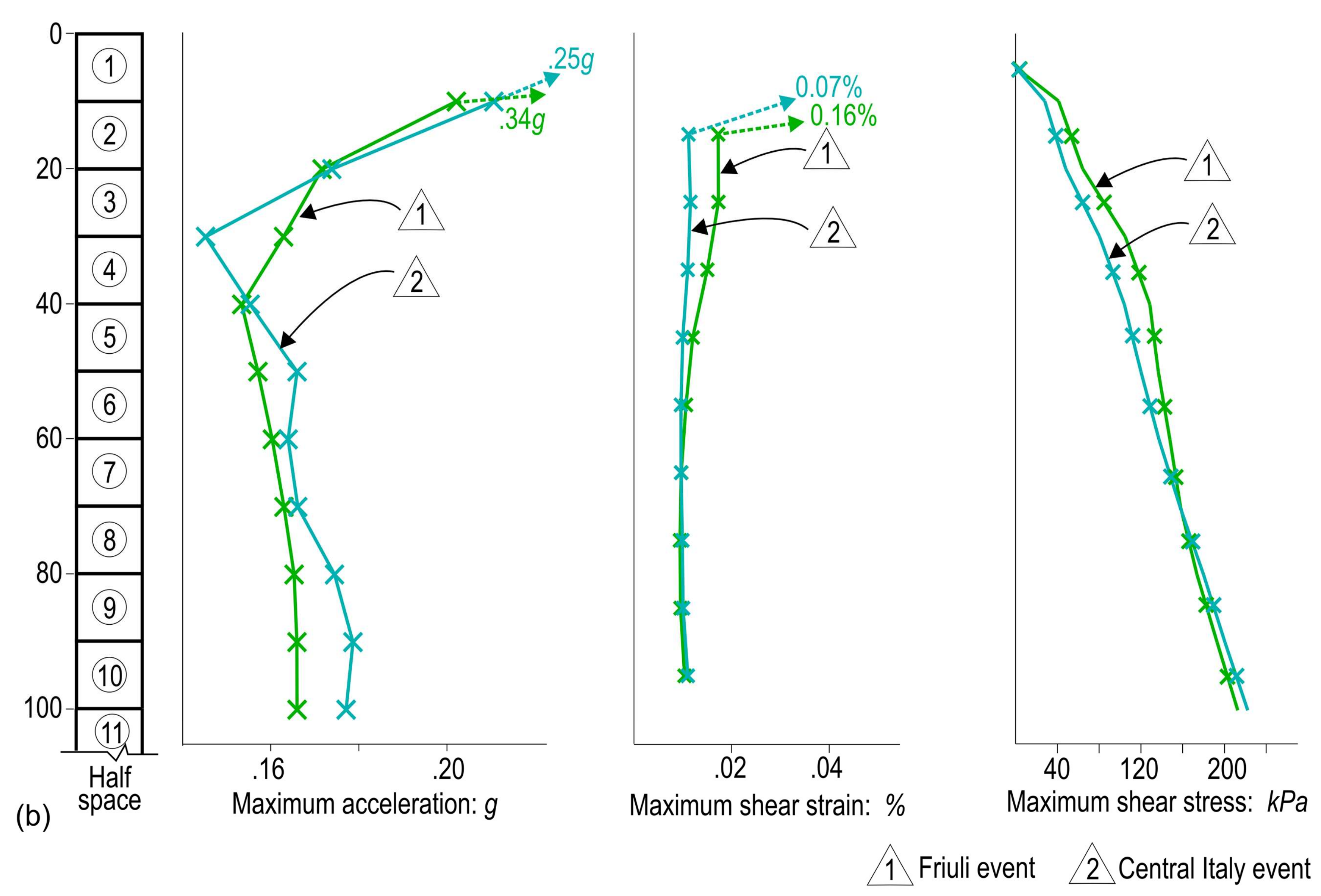


(b) Profile plot

Variation in Young's modulus with depth in foundation block: kPa; see slide #3 (a) for elevations.

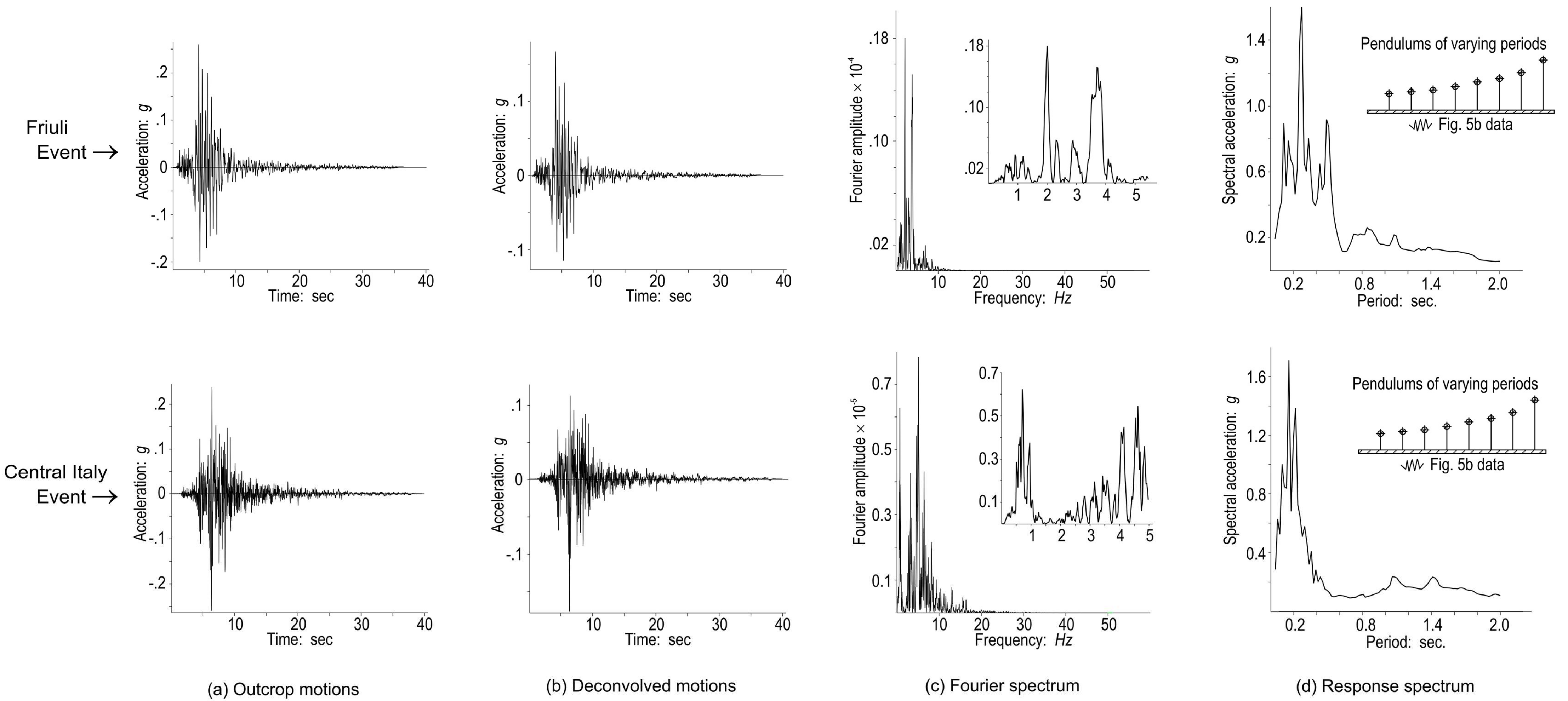


Numerical details for one-dimensional wave propagation analysis: (a) input data used;



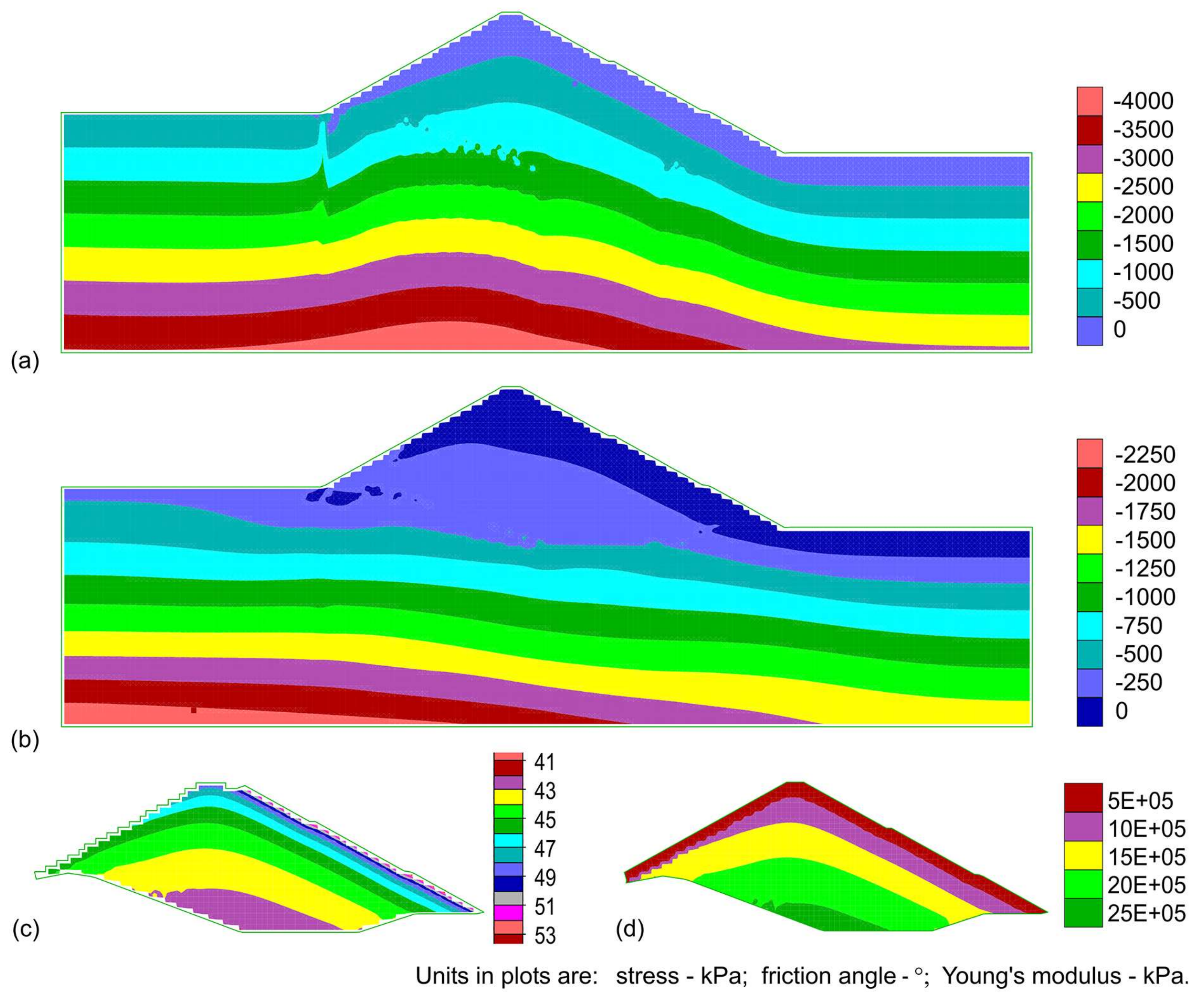
Numerical details for one-dimensional wave propagation analysis:

(b) results of interest.



Ground motions details Friuli and Central Italy events:

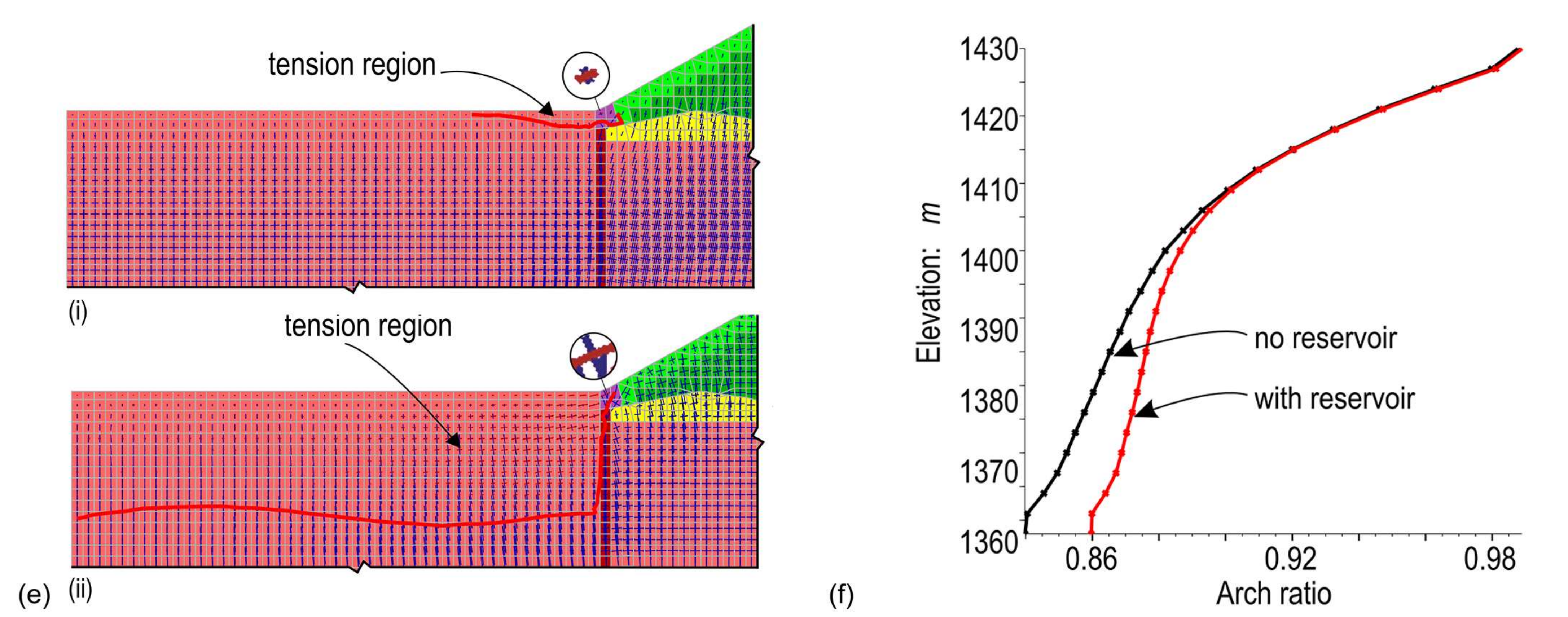
(a) outcrop motions; (b) deconvolved motions; (c) Fourier power spectrum of deconvolved motions in (b); (d) acceleration response spectrum of deconvolved motions in (b) – damping ratio = 0.



Static analysis results at the end of impoundment:

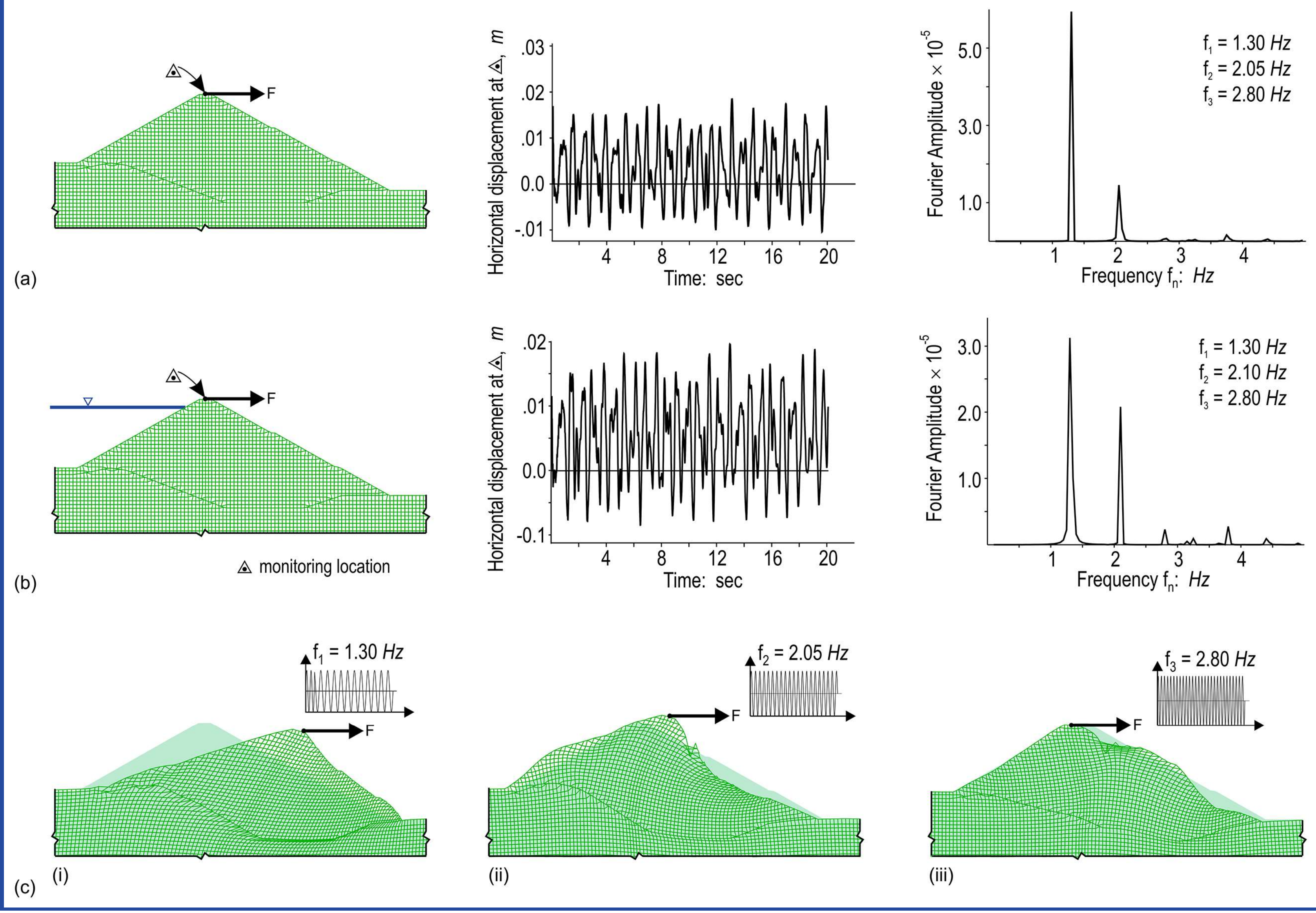
(a, b) contours of vertical and horizontal total stresses in the model;

(c, d) contours of angle of internal friction and Young's modulus in the embankment.



Static analysis results at the end of impoundment:
(e) zero contour of minor principal effective stress separating regions of tension and compression at the end of (i) construction and (ii) impoundment;
(f) arching ratio along the dam centerline at the end of construction and impoundment.

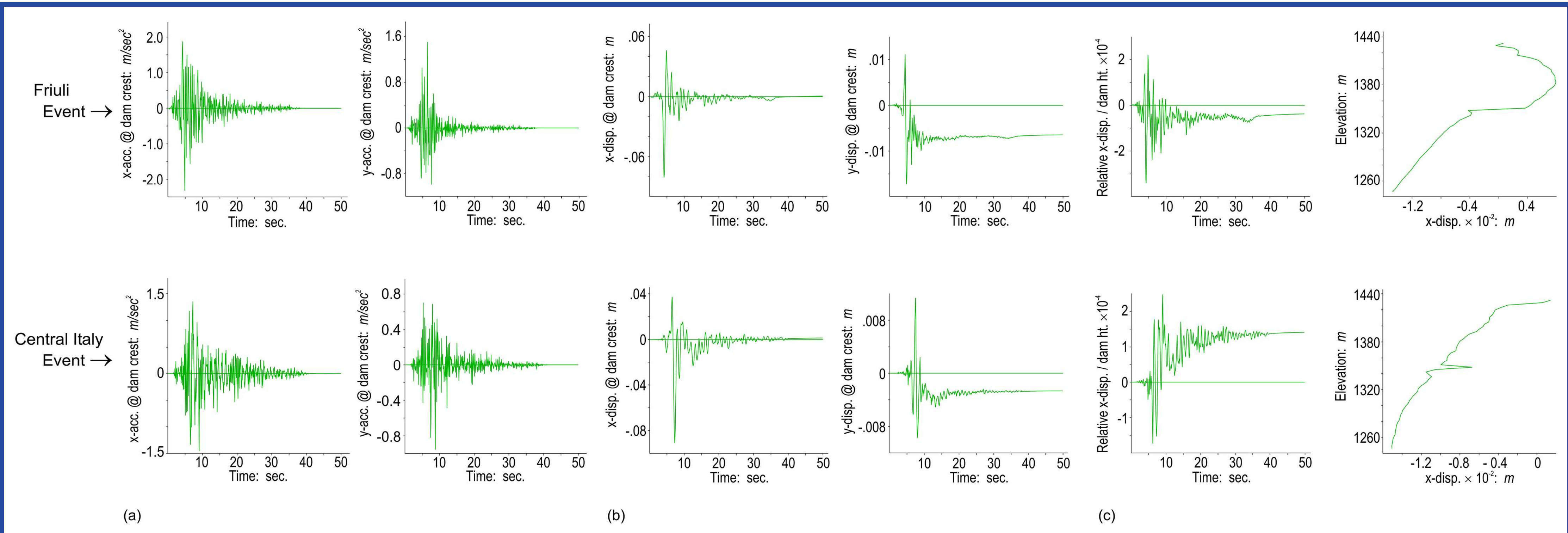
Natural vibration characteristics of Menta Dam in transverse (u/s – d/s) direction:



(a) problem setup and results for the end-of-construction condition;

(b) problem setup and results for RWL = 1424.5 condition;

(c) mode shapes for the end-of-construction condition.

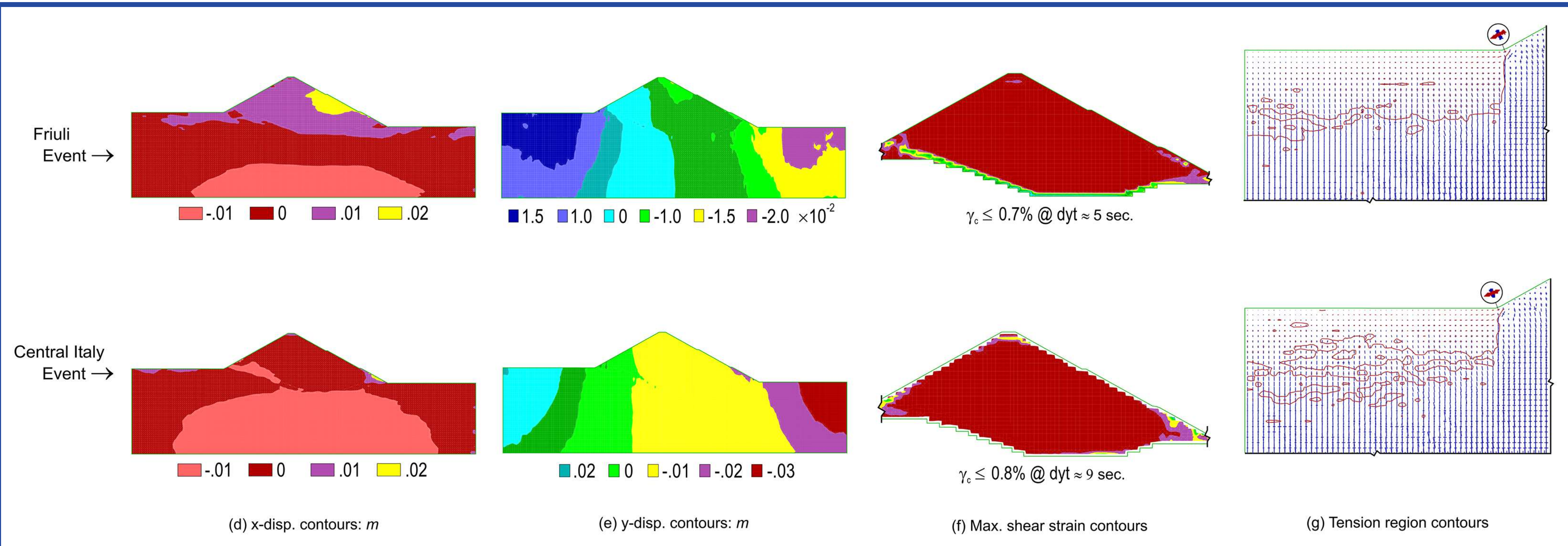


Dynamic analysis results for Friuli and Central Italy events:

(a) horizontal and vertical acceleration history at dam crest;

(b) horizontal and vertical displacement history at dam crest;

(c) relative horizontal displacement at dam crest/dam height and post-seismic horizontal displacement of the central axis of the dam

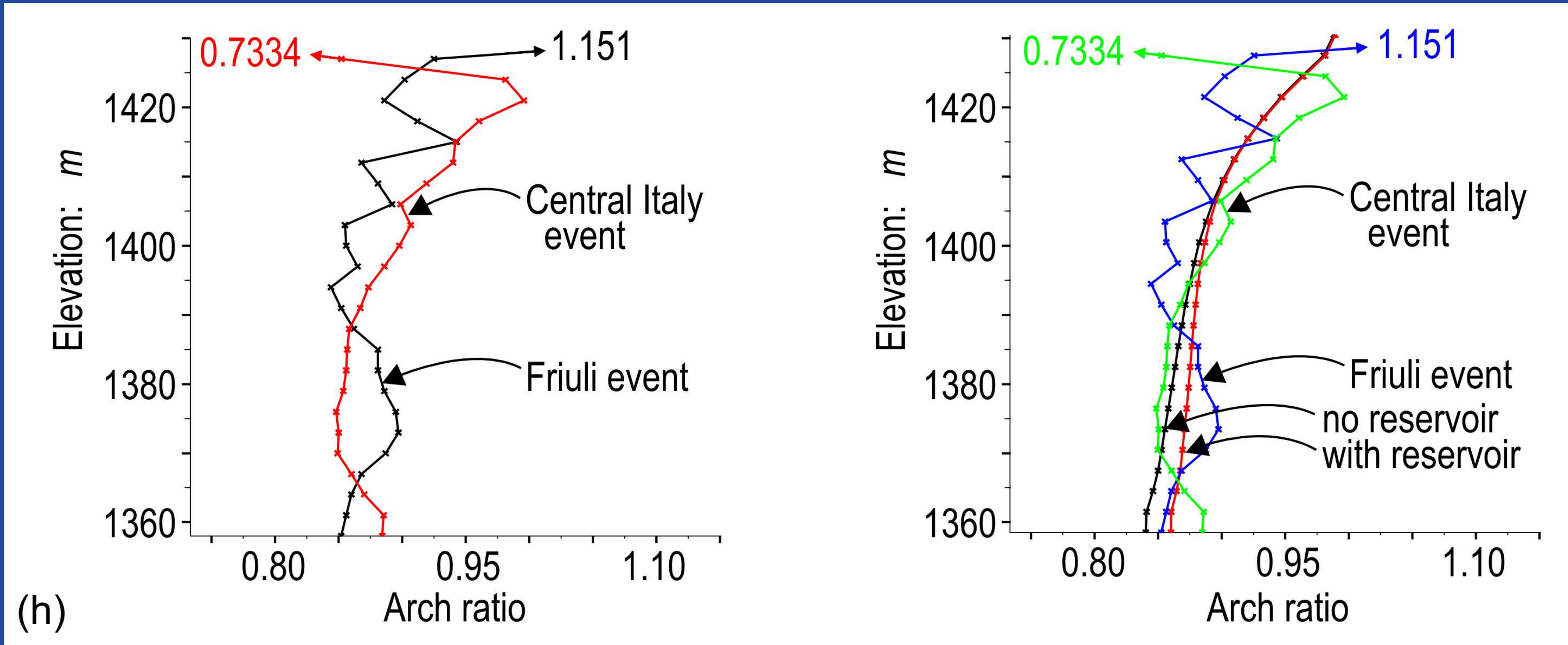


Dynamic analysis results for Friuli and Central Italy events:

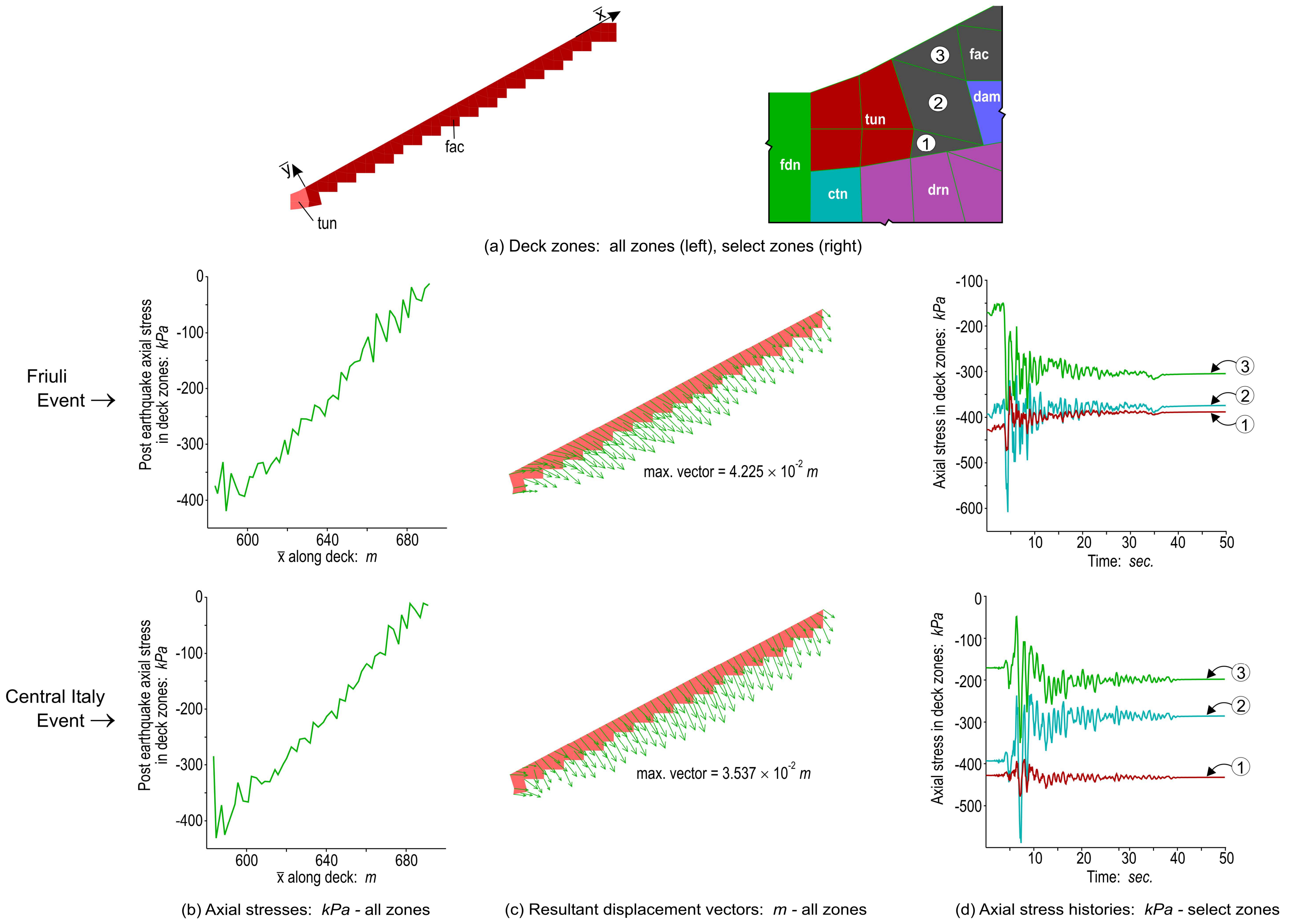
(d-e) post-seismic horizontal and vertical displacements;

(f) contours of maximum shear strain;

(g) post-seismic tension zones



Dynamic analysis results for Friuli and Central Italy events: post-seismic arching ratios for the two seismic events; and comparison with their counterparts in static analysis results; see slide #8 (f).



Post-seismic axial stress and displacement results in bituminous facing.

8 Summary

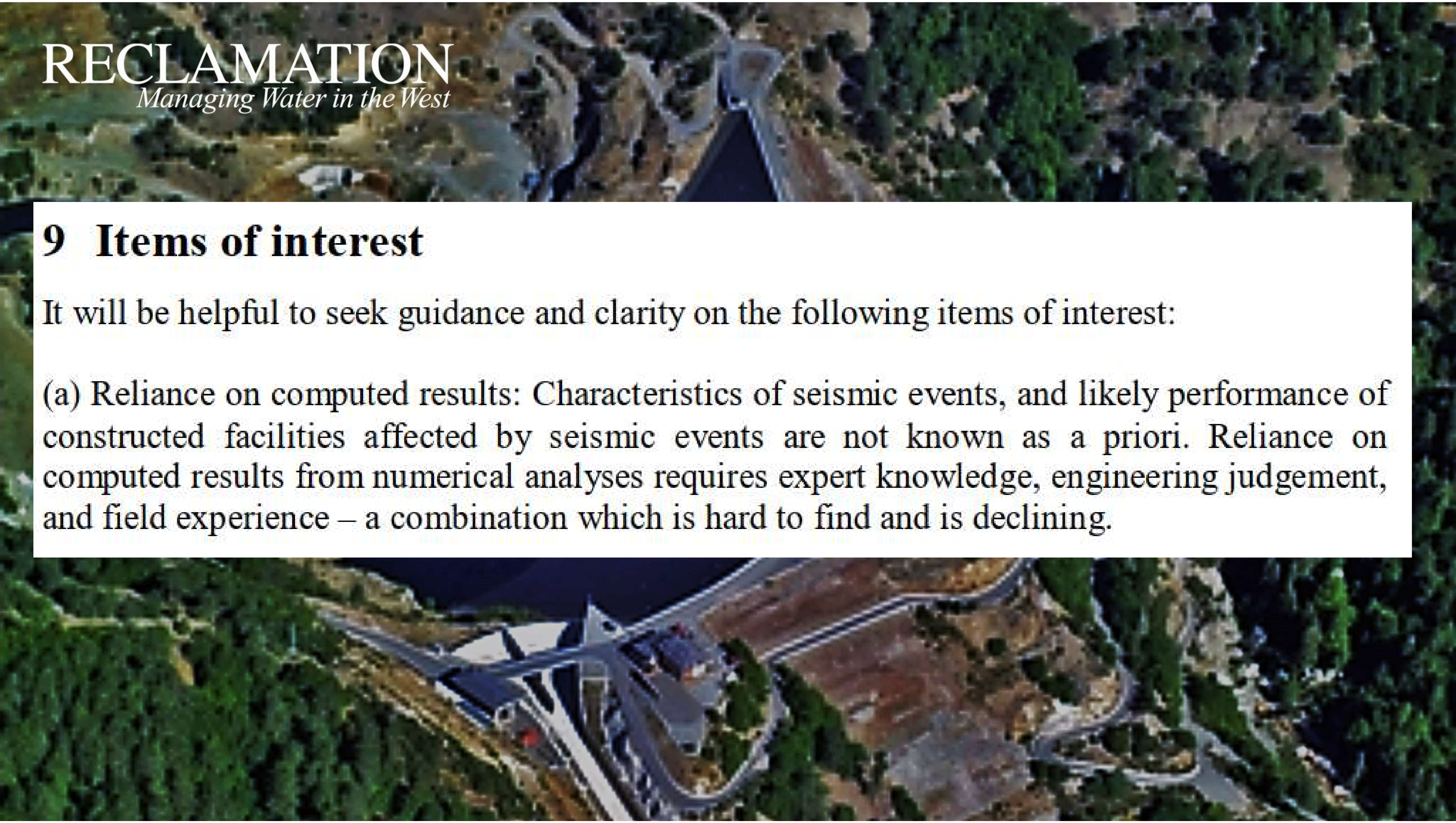
(a) Static analysis results indicate: (i) no seepage flow occurs through the rockfill dam; (ii) no seepage flow exits from the drainage layer; (iii) seepage flow occurs through the foundation rock; (iv) tension zones develop in the weathered foundation rock upstream of the dam toe; and (iv) arching occurs in the dam, i.e., the computed vertical stresses along the dam centerline are less than the nominal vertical stresses.

(b) Computed first natural frequency of the dam-foundation system is 1.3 Hz. Friuli and Central Italy events have frequencies which are close to the computed natural frequencies of the dam-foundation-reservoir system.

(c) Use of free field boundary conditions along the ±x face boundaries of the model leads to large deformations which result in bad geometry and termination of the dynamic analysis. The cause of this numerical instability was not well understood.

(d) Use of static boundary conditions on the ±x face boundaries allows dynamic analysis to run full duration of the event. Dynamic analyses were extended to run for 100 sec. with no sign of numerical difficulty or change in post-seismic analysis results.

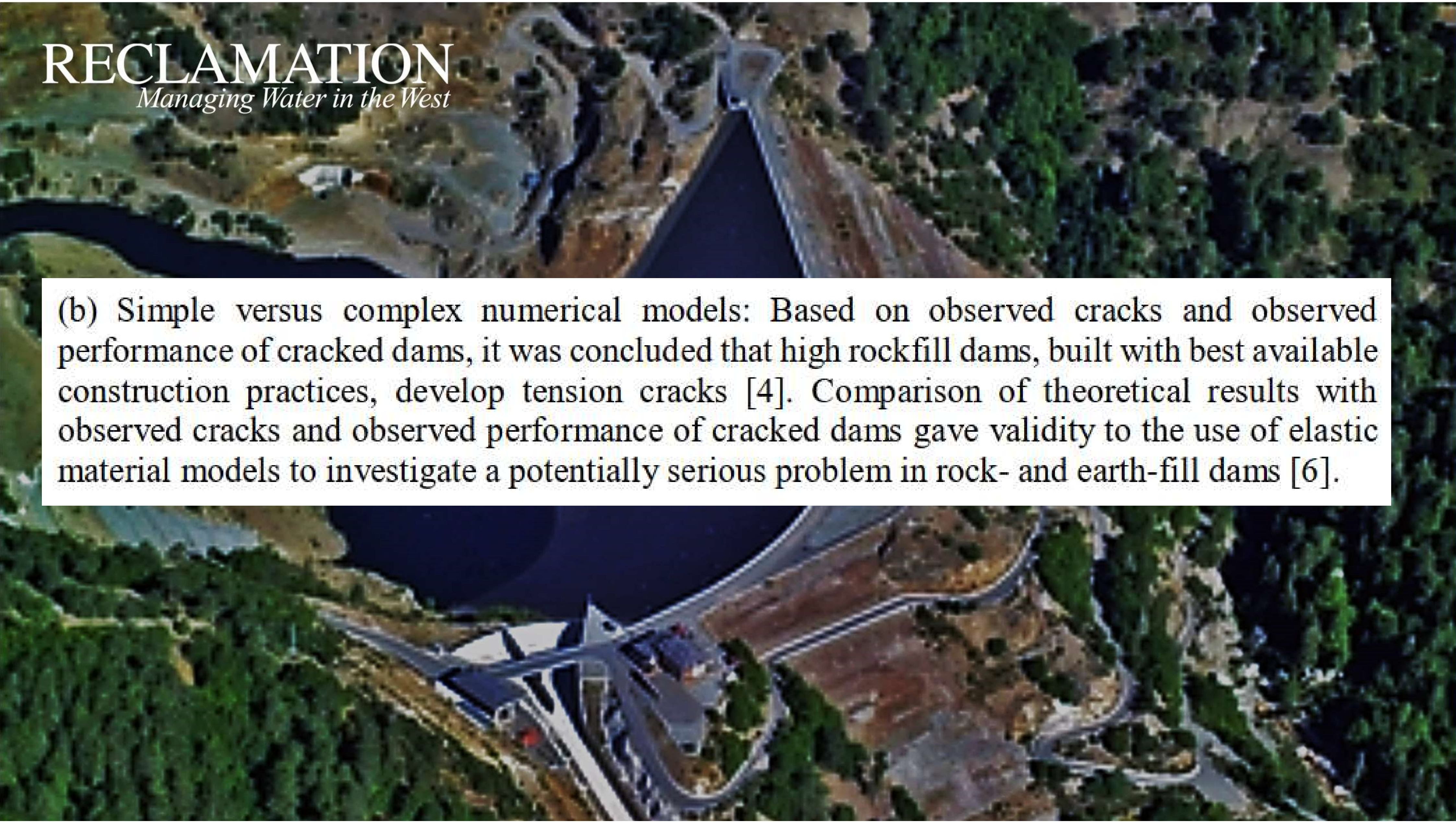
(e) The dynamic analysis results included herein show that tension zones develop in the foundation upstream of the grout curtain and the tunnel – the region encapsulating tension zones is identified by a single contour which separates regions of tension and compression. The principal stress tensors are shown as crosses – the red-cross lines indicate tensile stress, the blue-cross lines indicate compression. The orientations of the red-cross lines in Fig. 9(g) imply that the cracks are essentially in the vertical (up–down) direction.



9 Items of interest

It will be helpful to seek guidance and clarity on the following items of interest:

(a) Reliance on computed results: Characteristics of seismic events, and likely performance of constructed facilities affected by seismic events are not known as a priori. Reliance on computed results from numerical analyses requires expert knowledge, engineering judgement, and field experience – a combination which is hard to find and is declining.



(b) Simple versus complex numerical models: Based on observed cracks and observed performance of cracked dams, it was concluded that high rockfill dams, built with best available construction practices, develop tension cracks [4]. Comparison of theoretical results with observed cracks and observed performance of cracked dams gave validity to the use of elastic material models to investigate a potentially serious problem in rock- and earth-fill dams [6].