

ICADD 11

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*11th International Conference
on Analysis of Discontinuous Deformation*

Site Response Analysis with 2D-DDA

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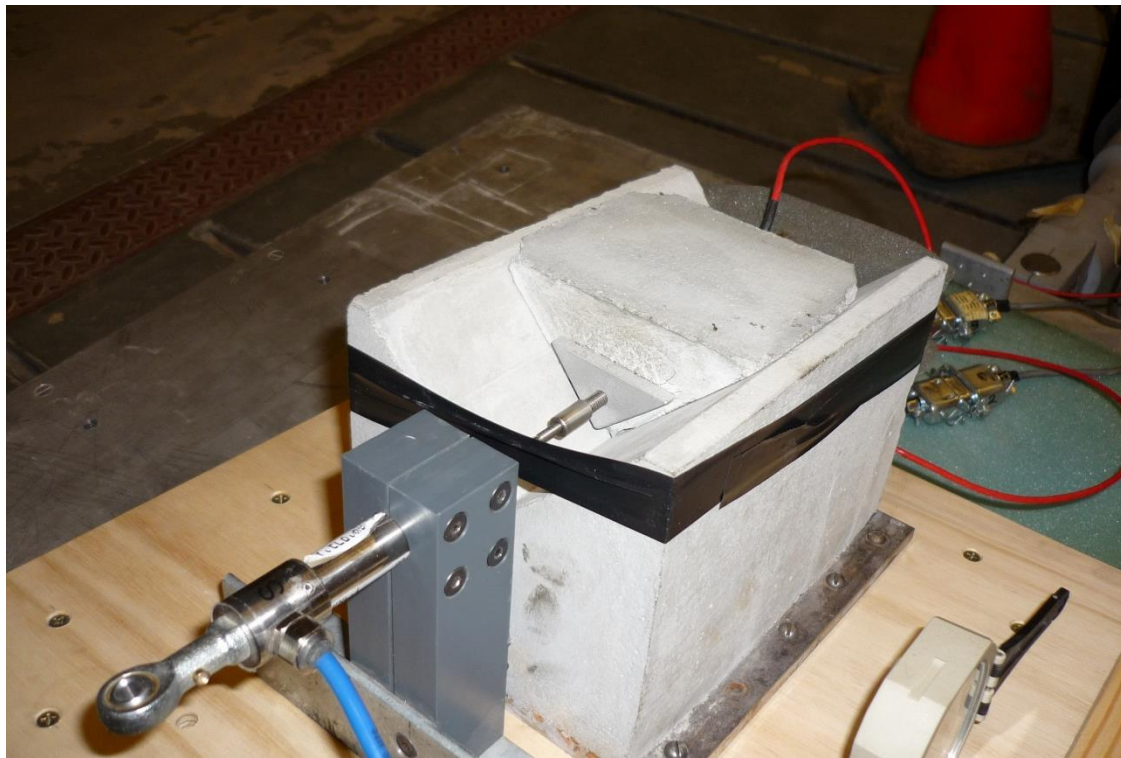
Dept. of Geological and Environmental Sciences

Ben-Gurion University of the Negev, Beer-Sheva, Israel



Talk Outline

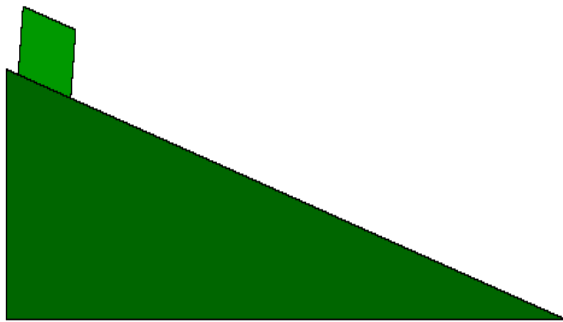
- ***Dynamic displacement of discrete elements: review of some published DDA verifications and validations***
 - Dynamic sliding on a single plane
 - Dynamic sliding of a wedge on two planes
 - Block response to dynamic shaking of foundations
 - Dynamic block rocking
- ***Accuracy of wave propagation modeling with DDA: recent results***
 - *P* wave propagation
 - *S* wave propagation
 - Site response analysis with DDA
- ***Case Study: The Western Wall Tunnels in Jerusalem – the significance of local site response***



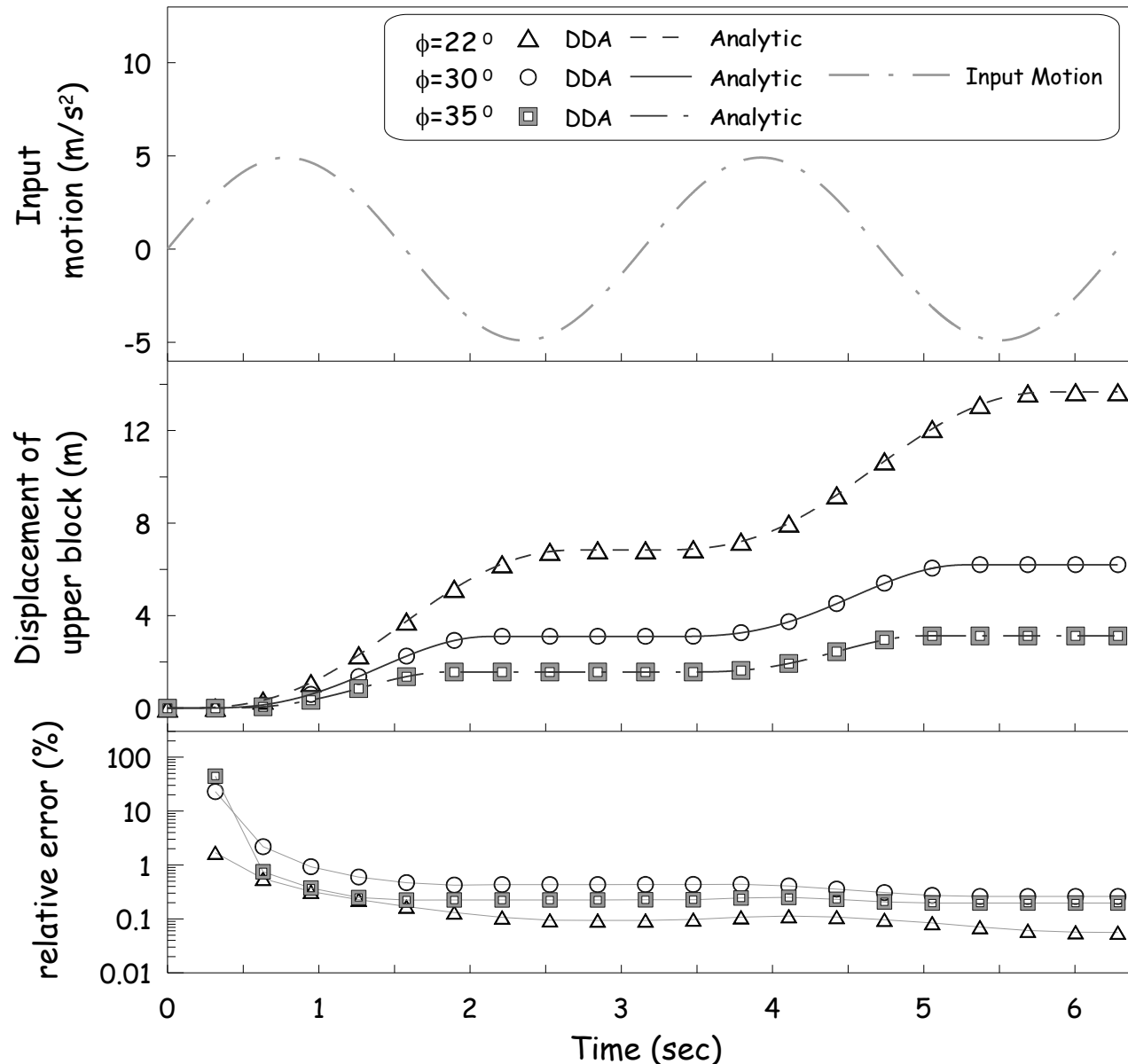
Dynamic Displacement of Discrete Elements with DDA: Verifications and Validations



Single Face Sliding

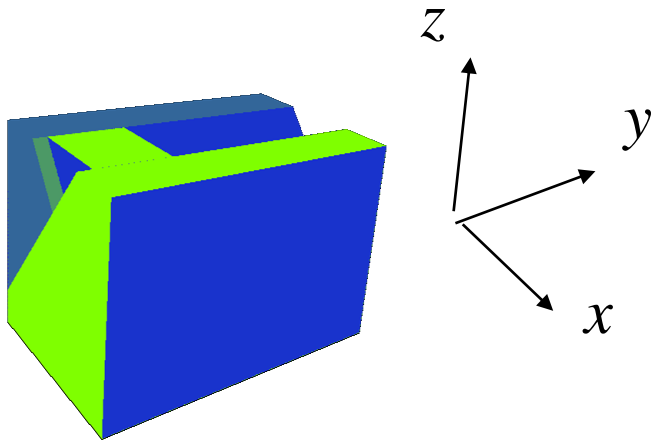


Dynamic sliding under gravitational load only was studied originally by Mary McLaughlin in her PhD thesis (1996) (Berkeley) and consequent publications with Sitar and Doolin 2004 - 2006. Sinusoidal input first studied by Hatzor and Feintuch (2001), *IJRMMS*. Improved 2D solution presented by Kamai and Hatzor (2008), *NAG*. Ning and Zhao (2012), *NAG* (From NTU) recently published a very detailed study of this problem.





Double Face Sliding



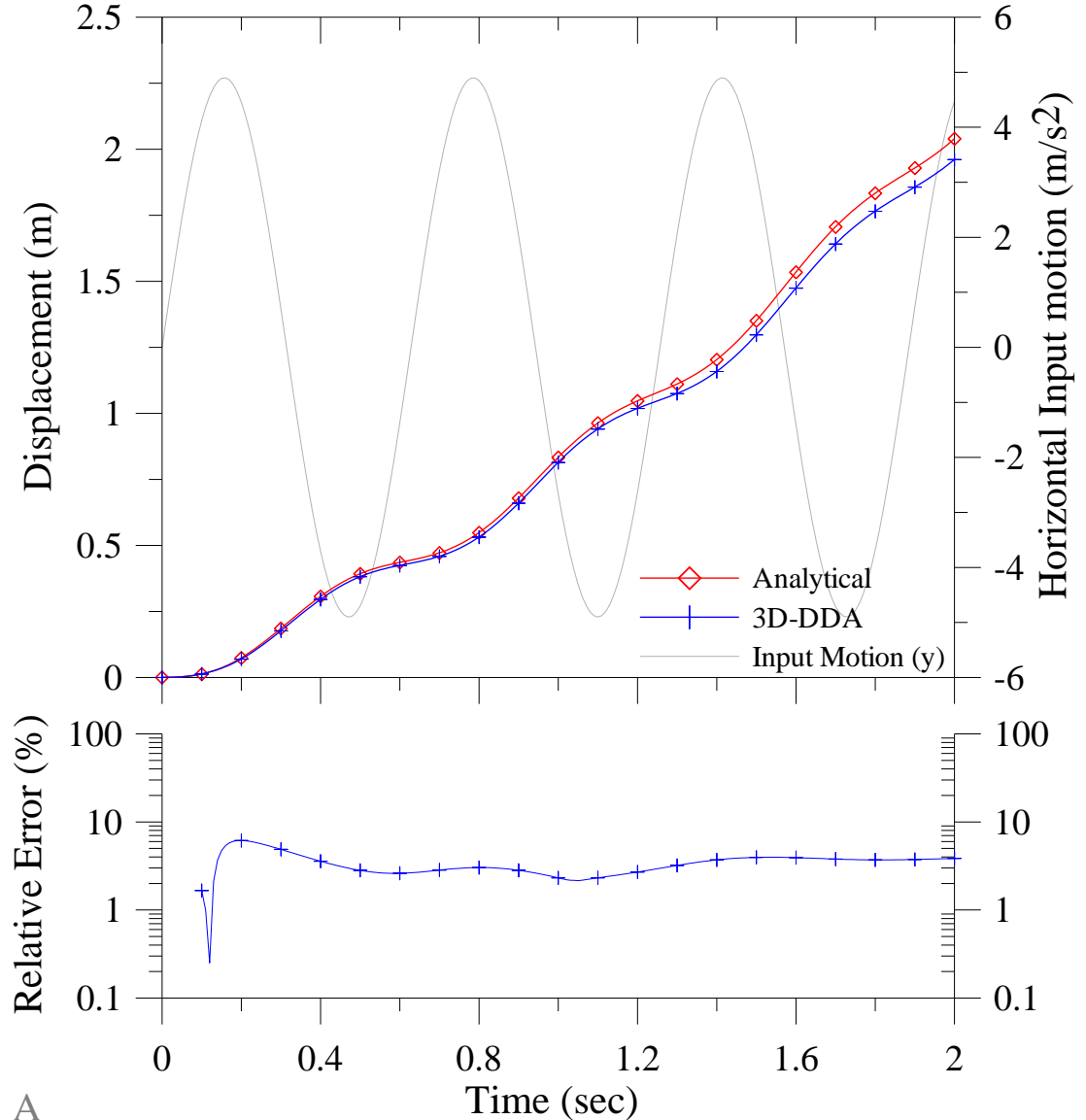
Wedge parameters:

$$P_1=52/063, P_2=52/296$$

$$\phi_1=\phi_2=30^\circ$$

DDA validation originally investigated by Yeung M. R., Jiang Q. H., Sun N., (2003) *IJRMMS* using physical tests.

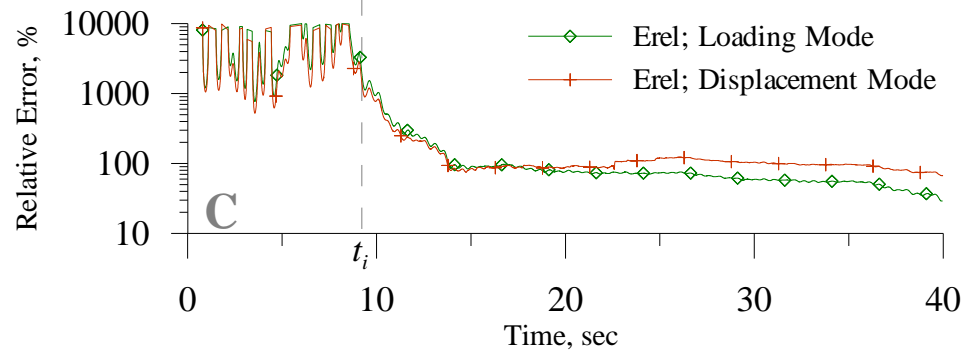
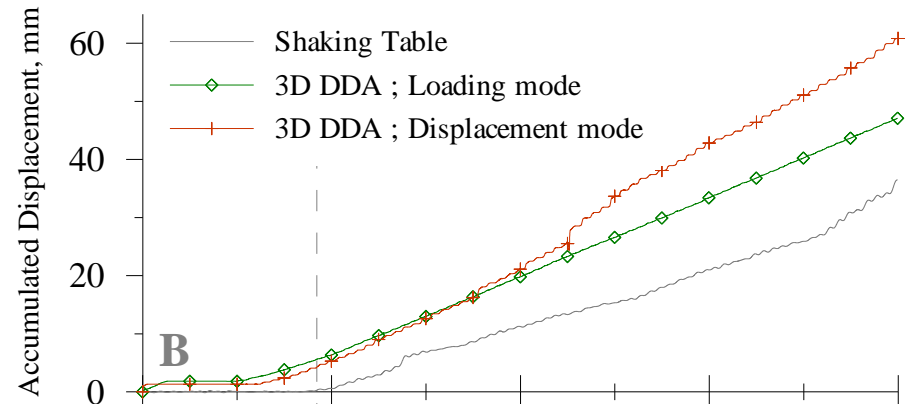
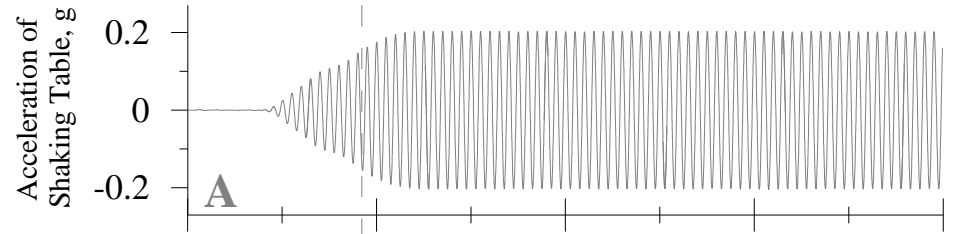
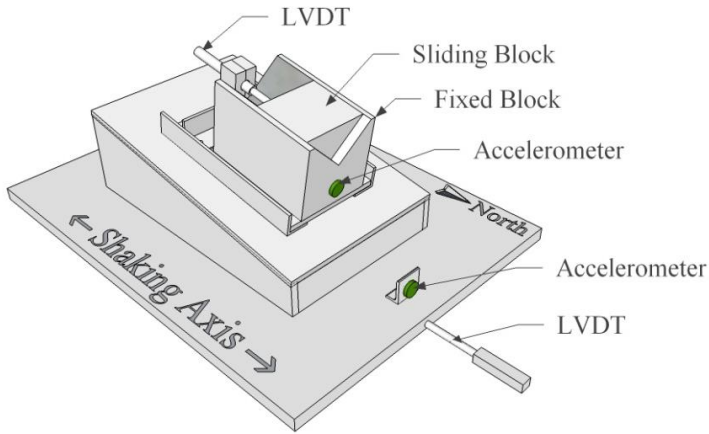
Analytical solution proposed and 3D DDA validation performed by Bakun-Mazor, Hatzor, and Glaser (2012), *NAG*.



A

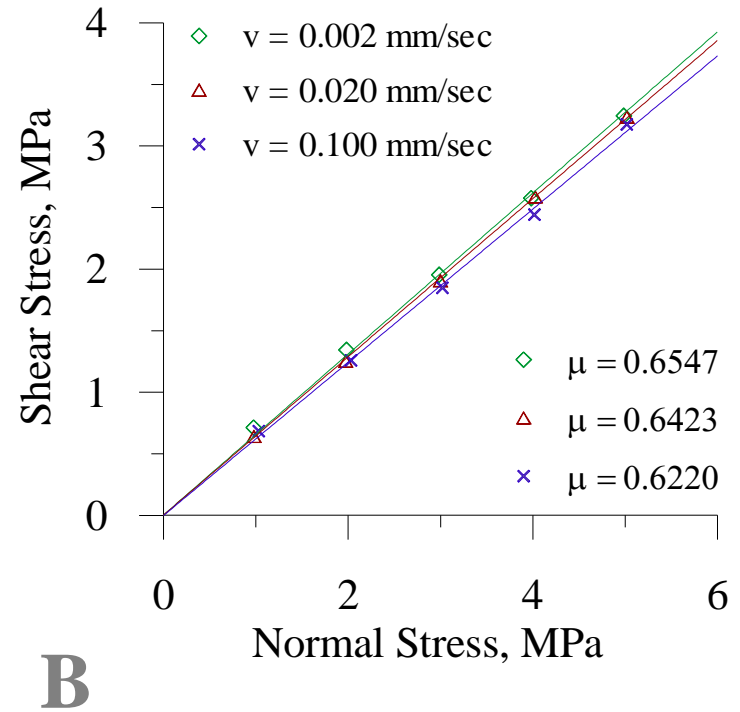
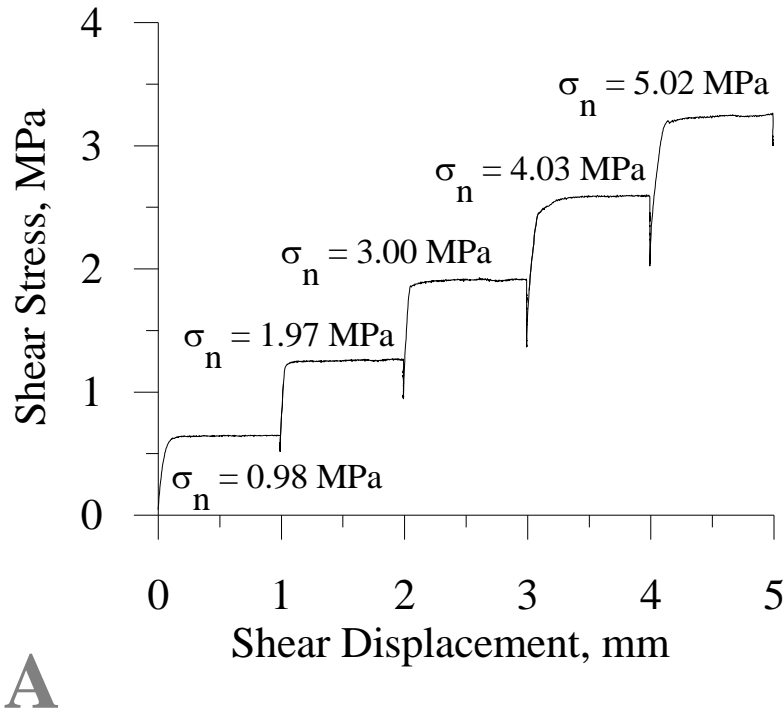
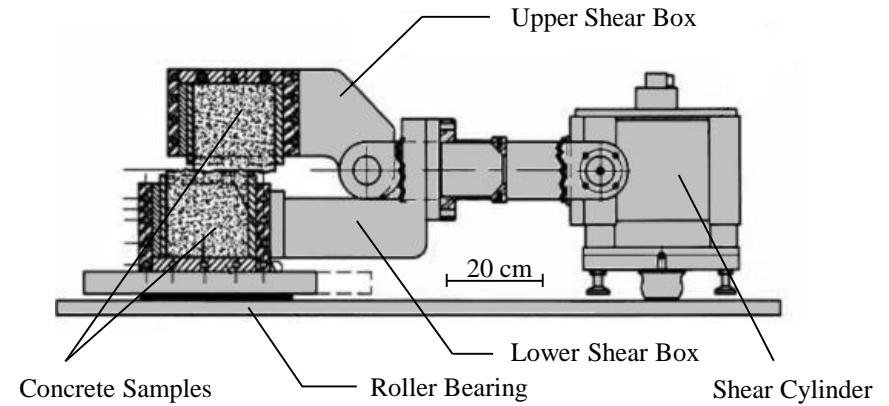
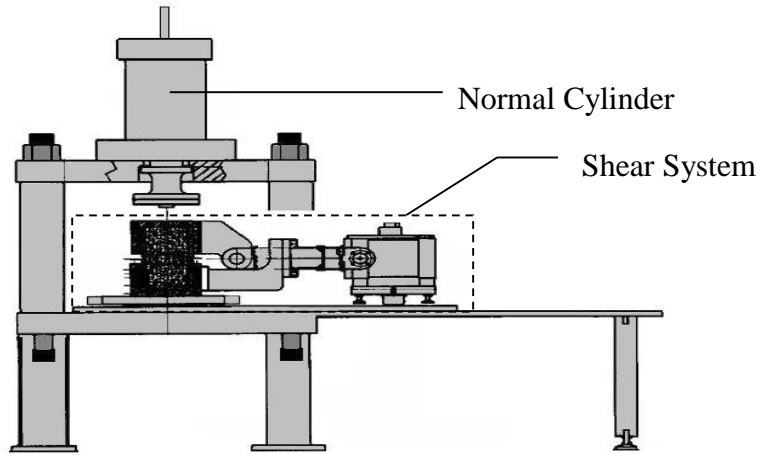


Shaking Table Experiments



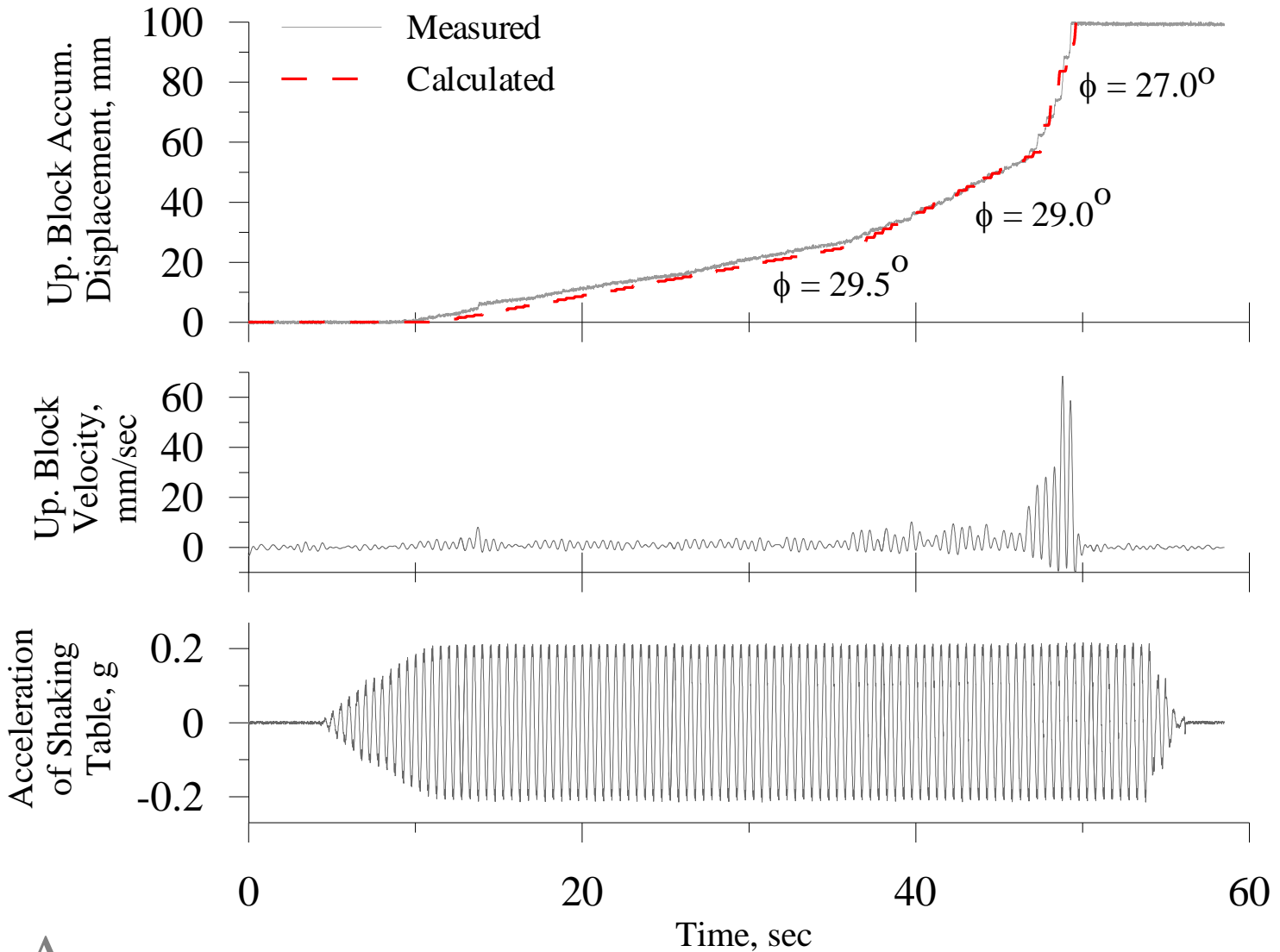


Rate Dependent Friction





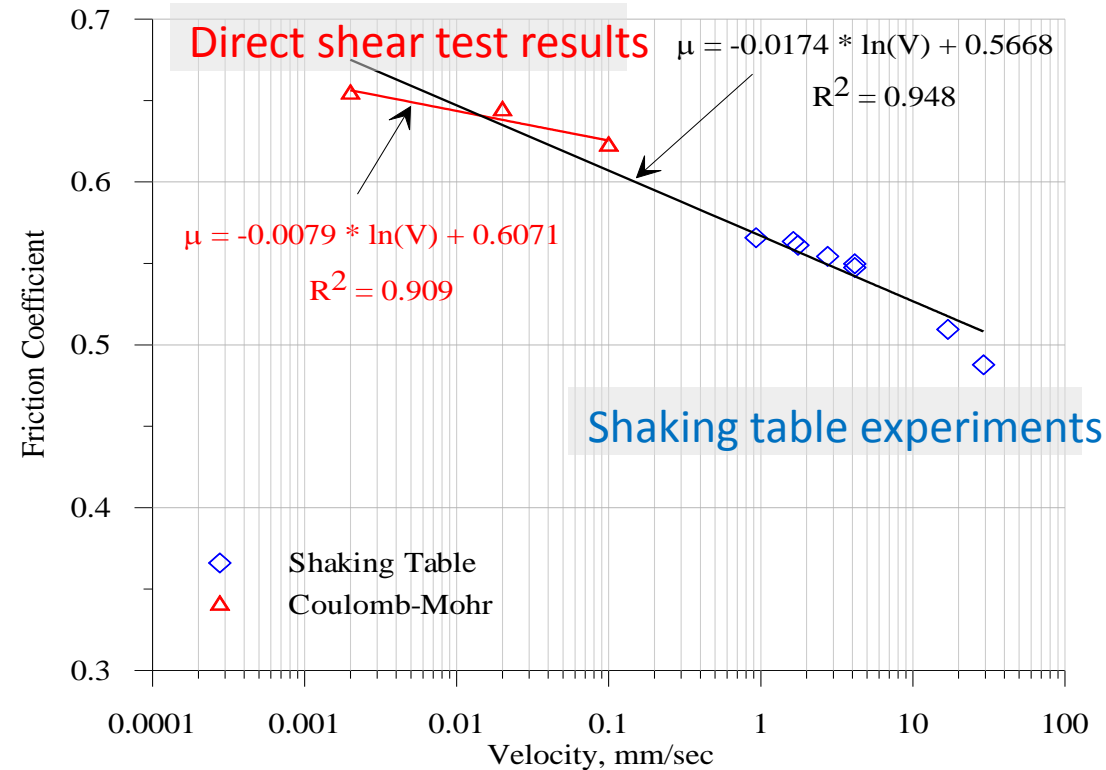
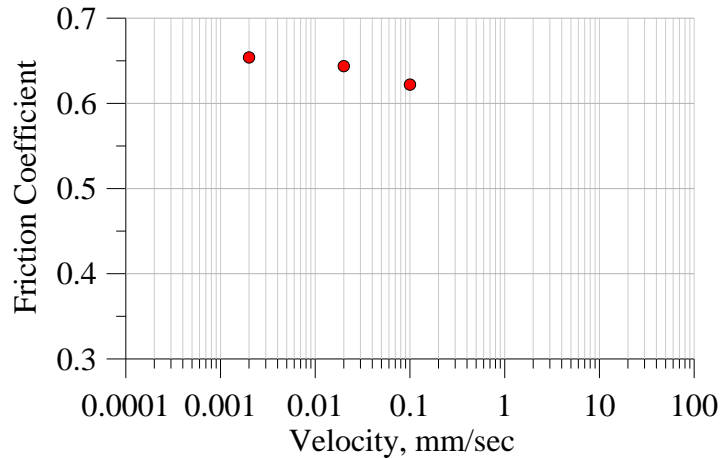
Observed Block "Run-out"



A



Friction Angle Degradation



Conclusion: frictional resistance of geological sliding interfaces may exhibit both velocity dependence as well as degradation as a function of velocity and/or displacement. This is particularly relevant for dynamic analysis of landslides, where sliding is assumed to have taken place under high velocities. Therefore, a modification of DDA to account for friction angle degradation is called for. This has already been suggested by Sitar et al. (2005), *JGGE –ASCE*; a new approach has recently been proposed by LZ Wang et al. (in press), *COGE* (from Zhejiang University).

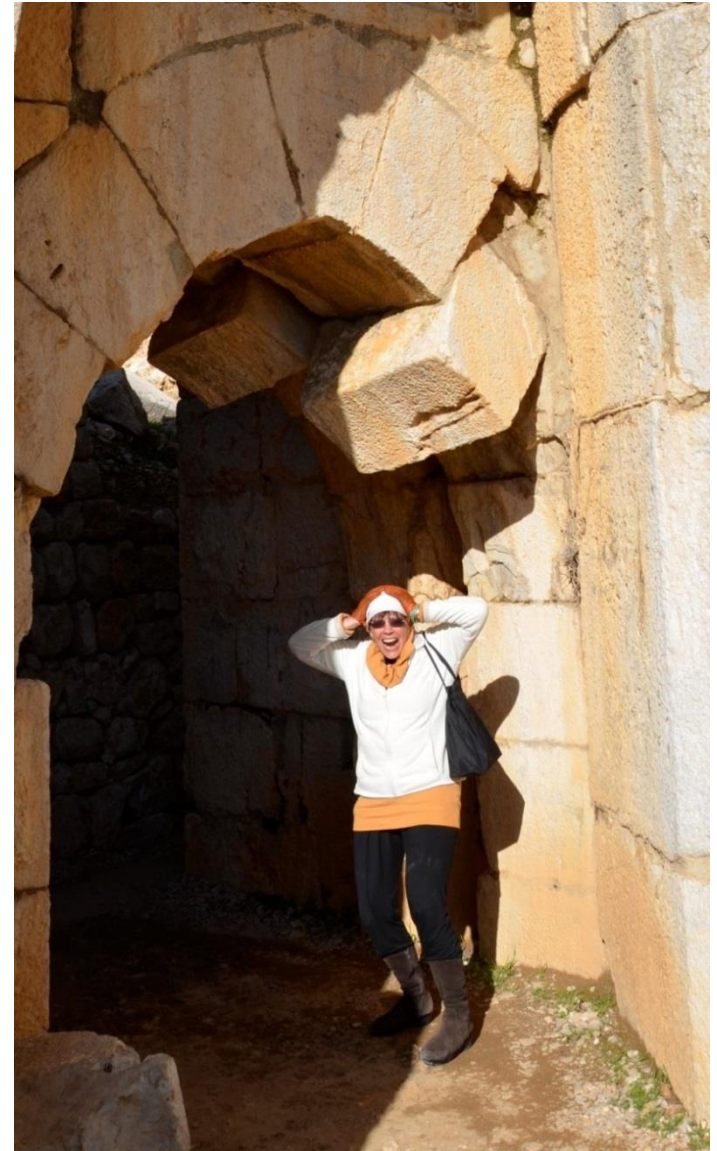


Dynamic interaction of discrete blocks

The dynamic interaction between discrete blocks subjected to dynamic loads such as earthquake vibrations is of high importance in seismic risk studies both for preservation of historic monuments as well as geotechnical earthquake engineering design.

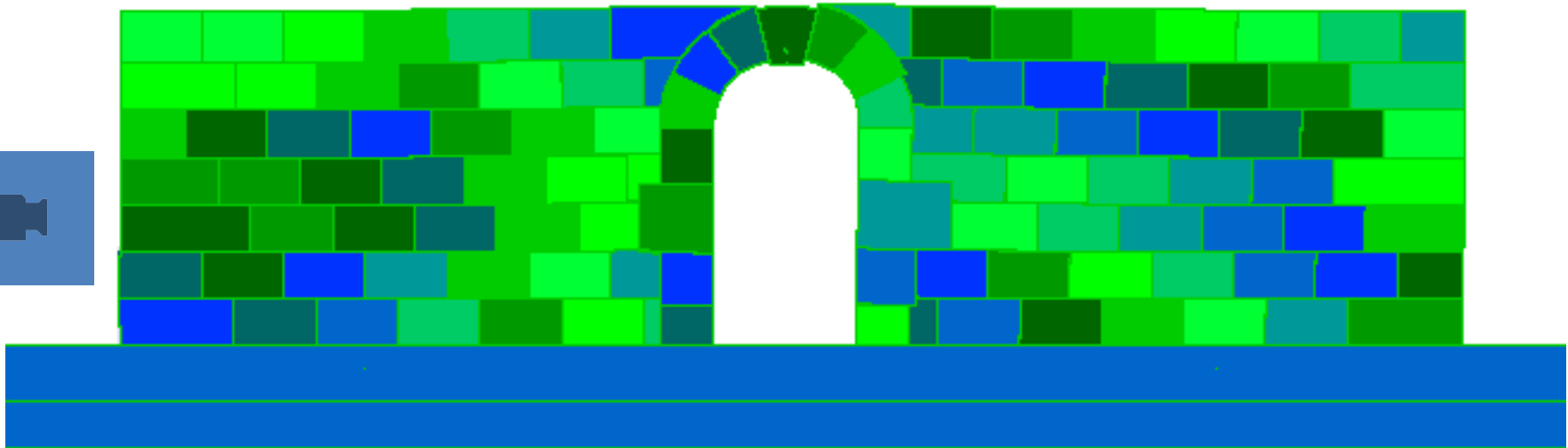
Several DDA research groups have begun to explore this issue. Notably, Professor Yuzo Ohnishi's DDA research group has recently made some important contributions to this field, e.g. Miki et al. (2010), *IJCM*; Sasaki et al. (2011), *IJCM*.

Kamai and Hatzor (2008), *NAG*, have suggested to use this approach to constrain the paleoseismic PGA in seismic regions by back analysis of stone displacements in historic masonry structures.



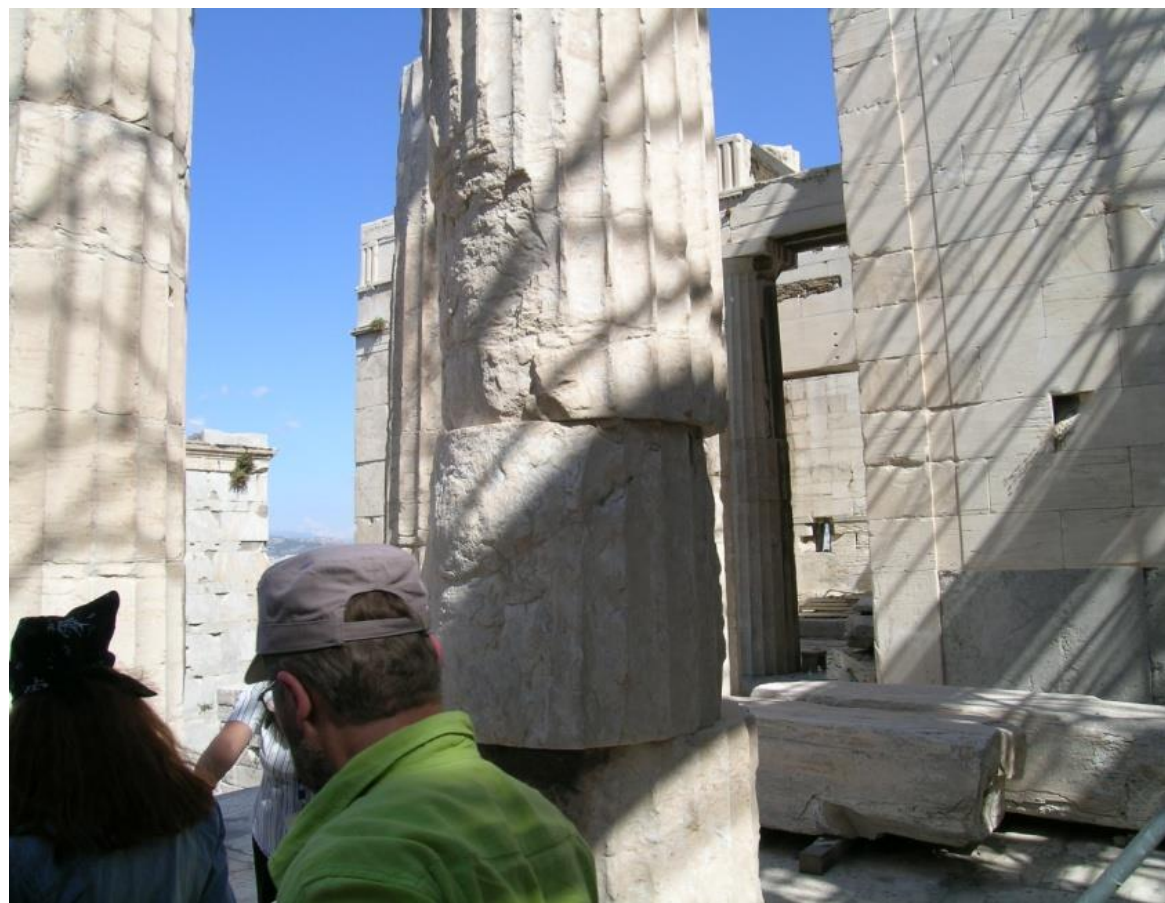


Direct *acceleration*
input simultaneously
to all blocks: we call it
“*QUAKE*” mode



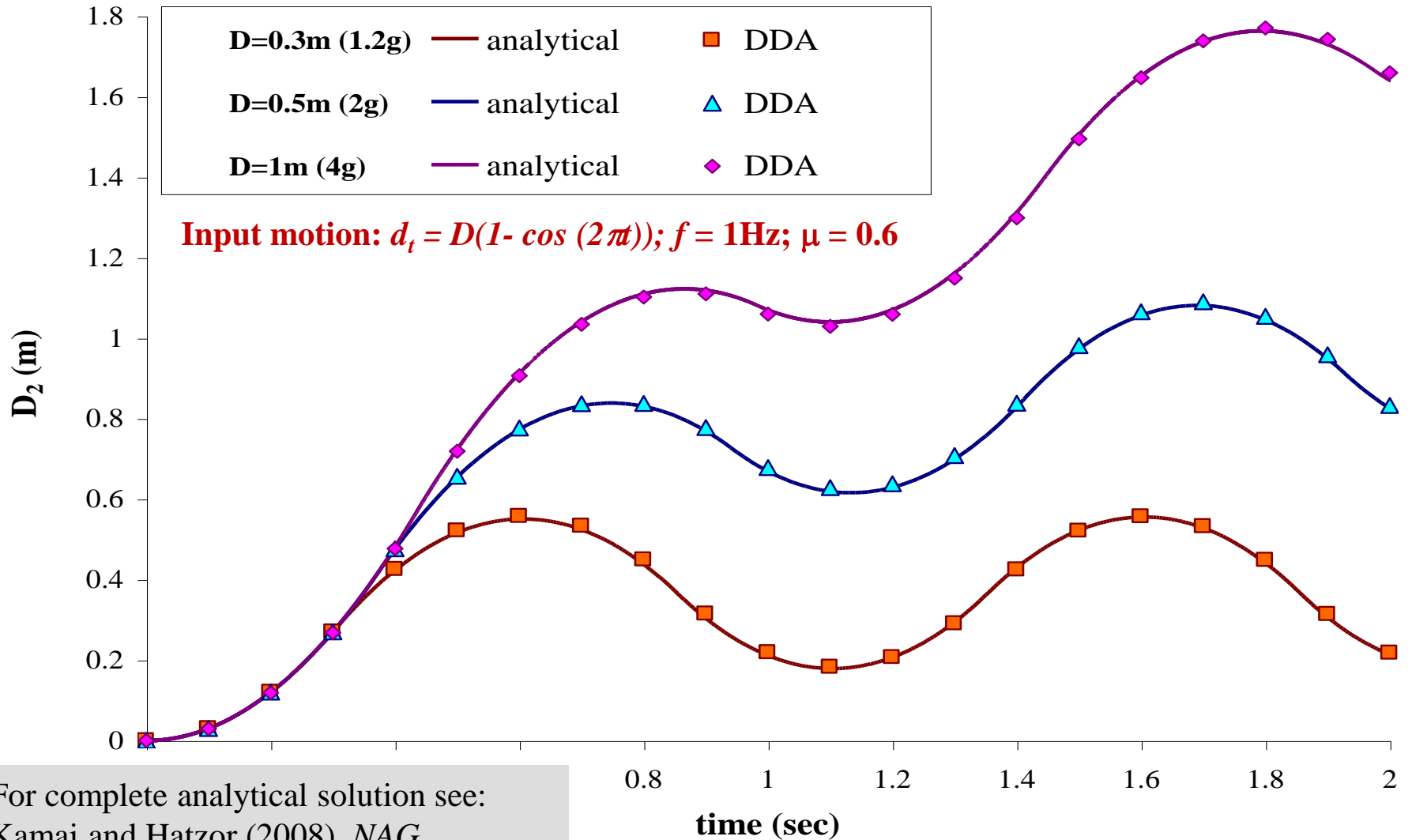


Direct
displacement input
to foundation
block: we call it
“*DISP*” mode





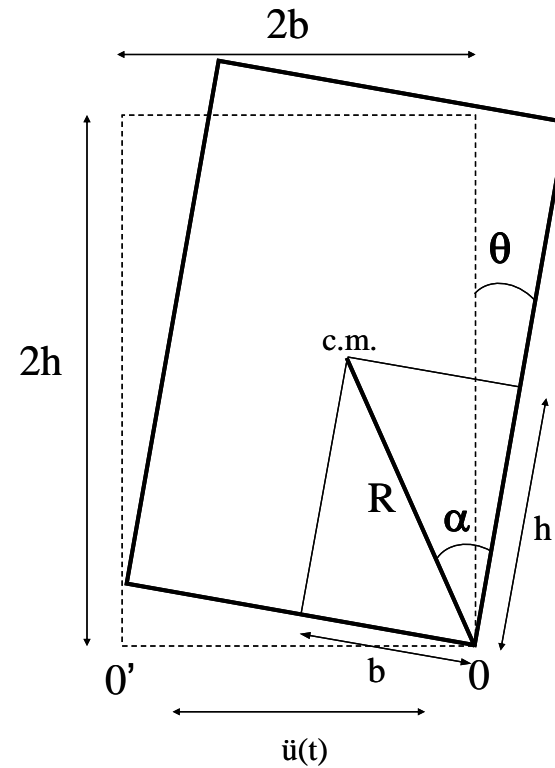
Response of overriding block to cyclic motion of foundation block: *DISP* mode



For complete analytical solution see:
Kamai and Hatzor (2008), *NAG*.



Dynamic Block Rocking: *QUAKE* mode

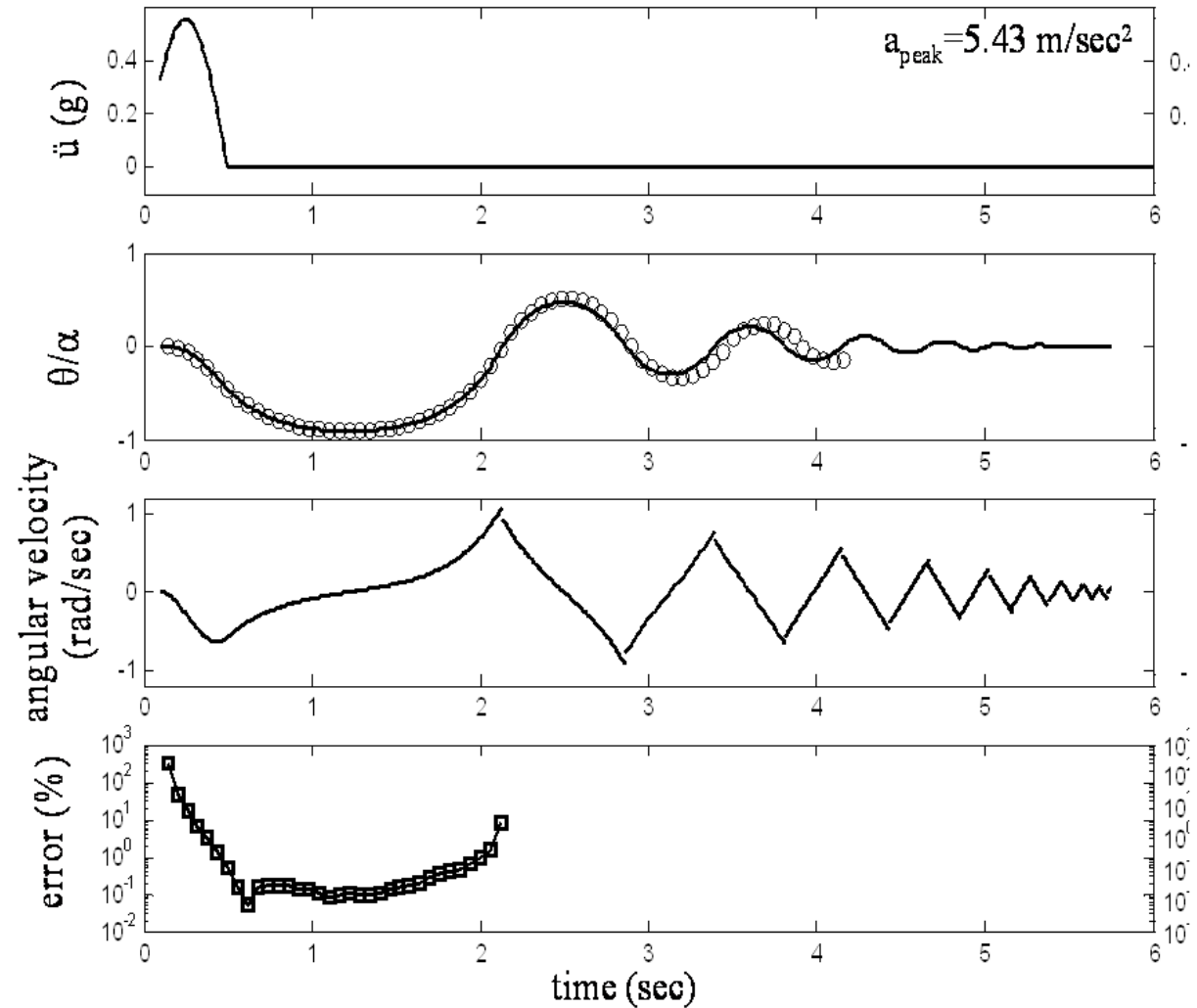
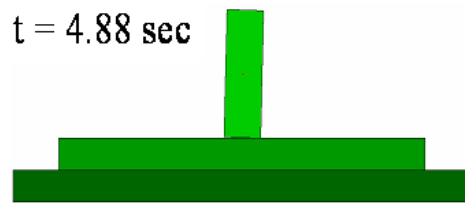
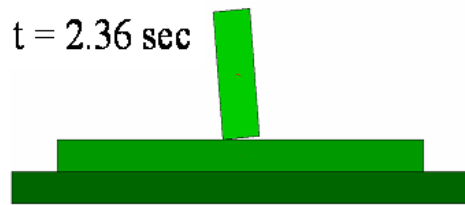
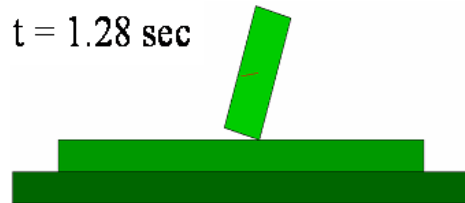
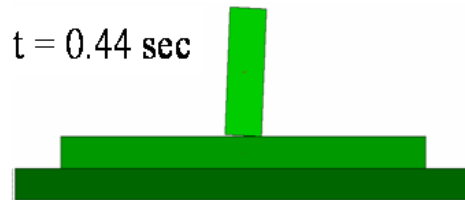


Analytical solution proposed by:
Makris and Roussos (2000), *Geotechnique*.

DDA validation with applications:
Yagoda-Biran and Hatzor (2010), *EESD*.

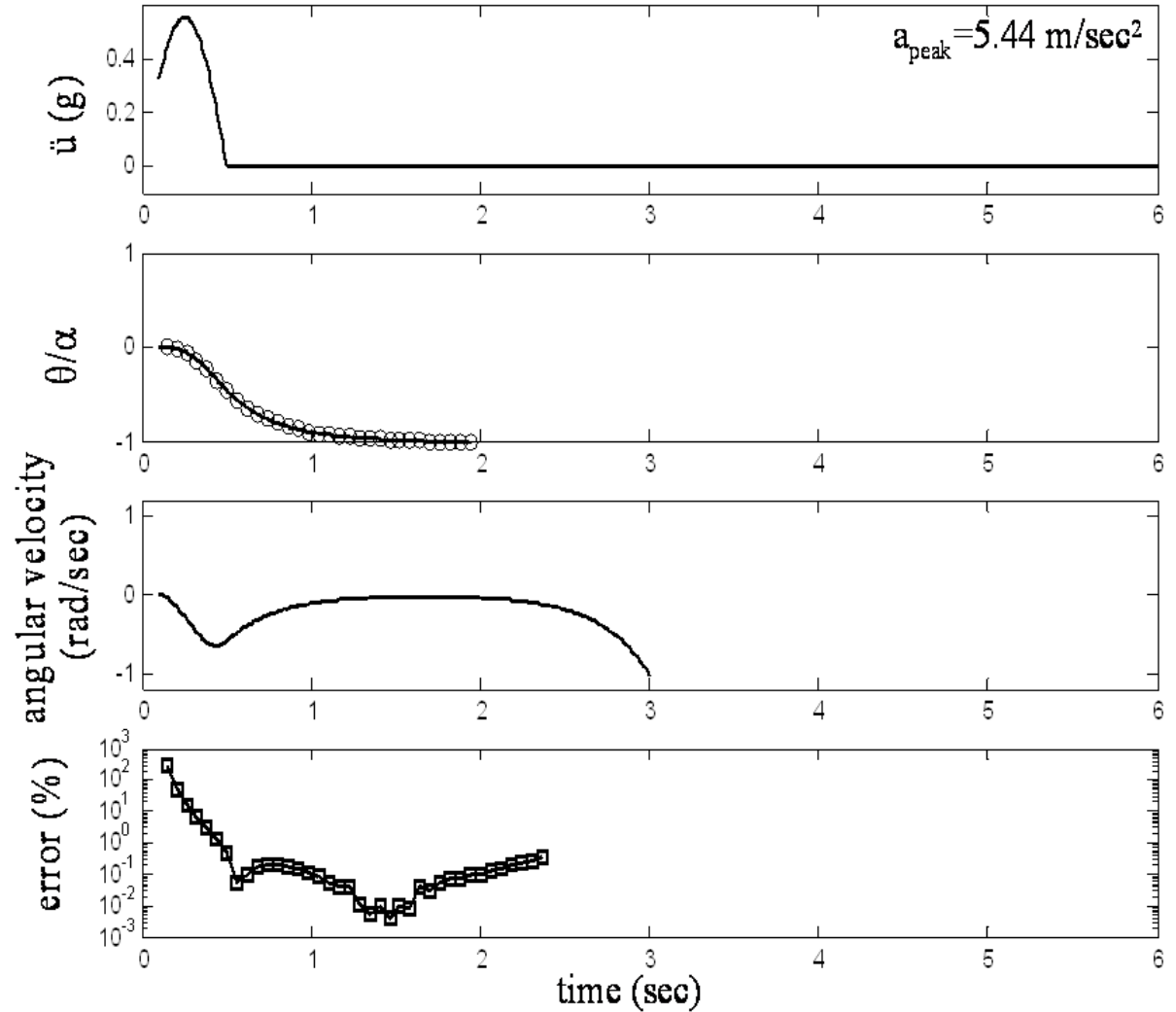
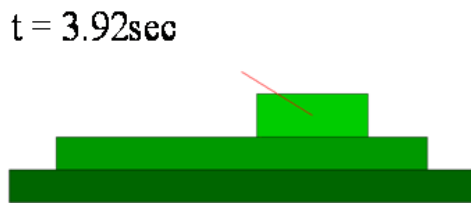
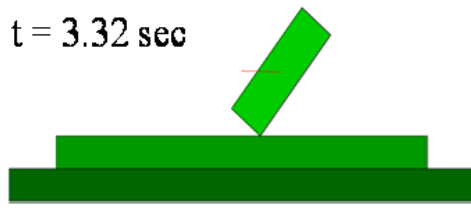
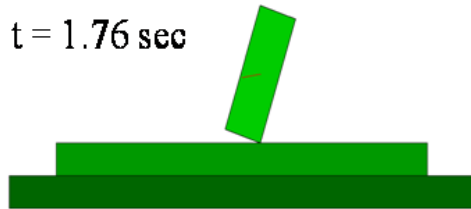
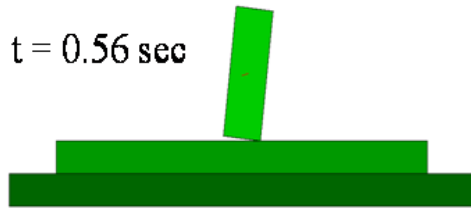


a_{peak} slightly lower than PGA required for toppling





a_{peak} slightly higher than PGA required for toppling

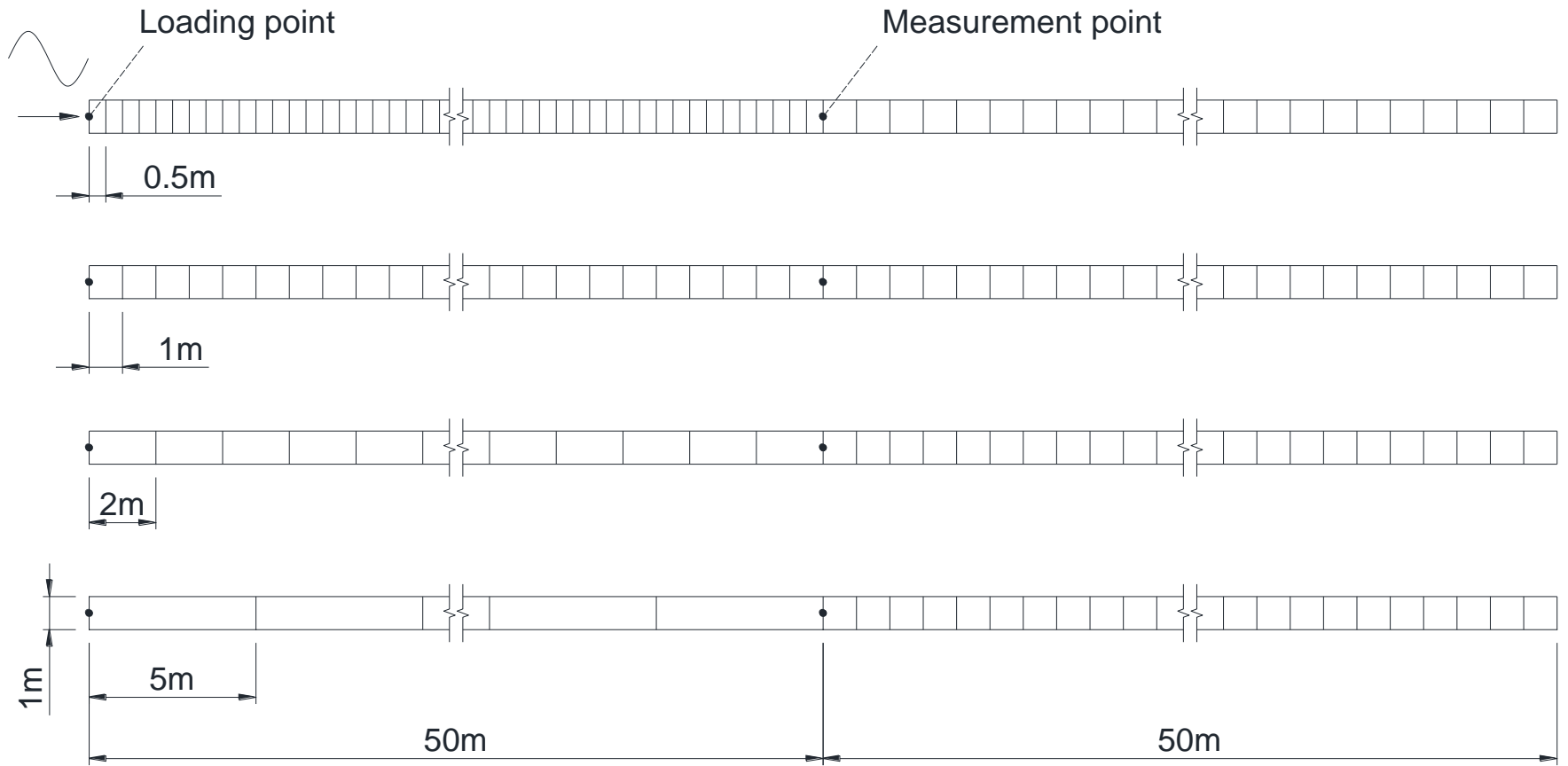




Accuracy of Wave Propagation Modeling with DDA: Benchmark Tests and Field Investigations



DDA accuracy in simulations of *P* wave propagation: 1D elastic bar

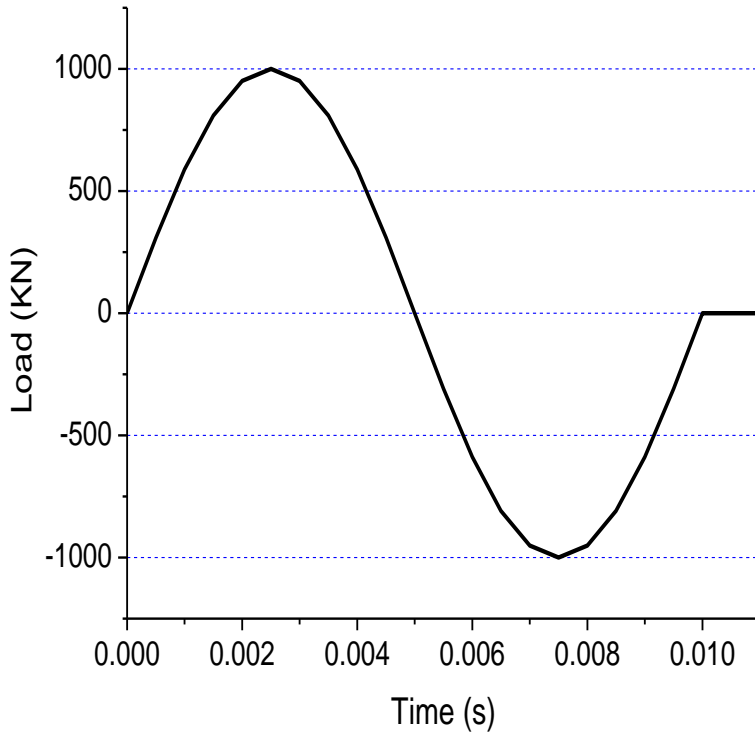


Work in progress with Huirong Bao , Xin Huang, and Ravit Zelig



Input function for P wave and model properties

$$F(t) = 1000 \sin(200\pi t) \text{ [KN]}$$



Block material	Unit mass (kg/m³)	2650
	Young's modulus (GPa)	50
	Poisson ratio	0.25
Joint material	Friction angle	35°
	Cohesion (MPa)	24
	Tensile strength (MPa)	18

Time history of input load

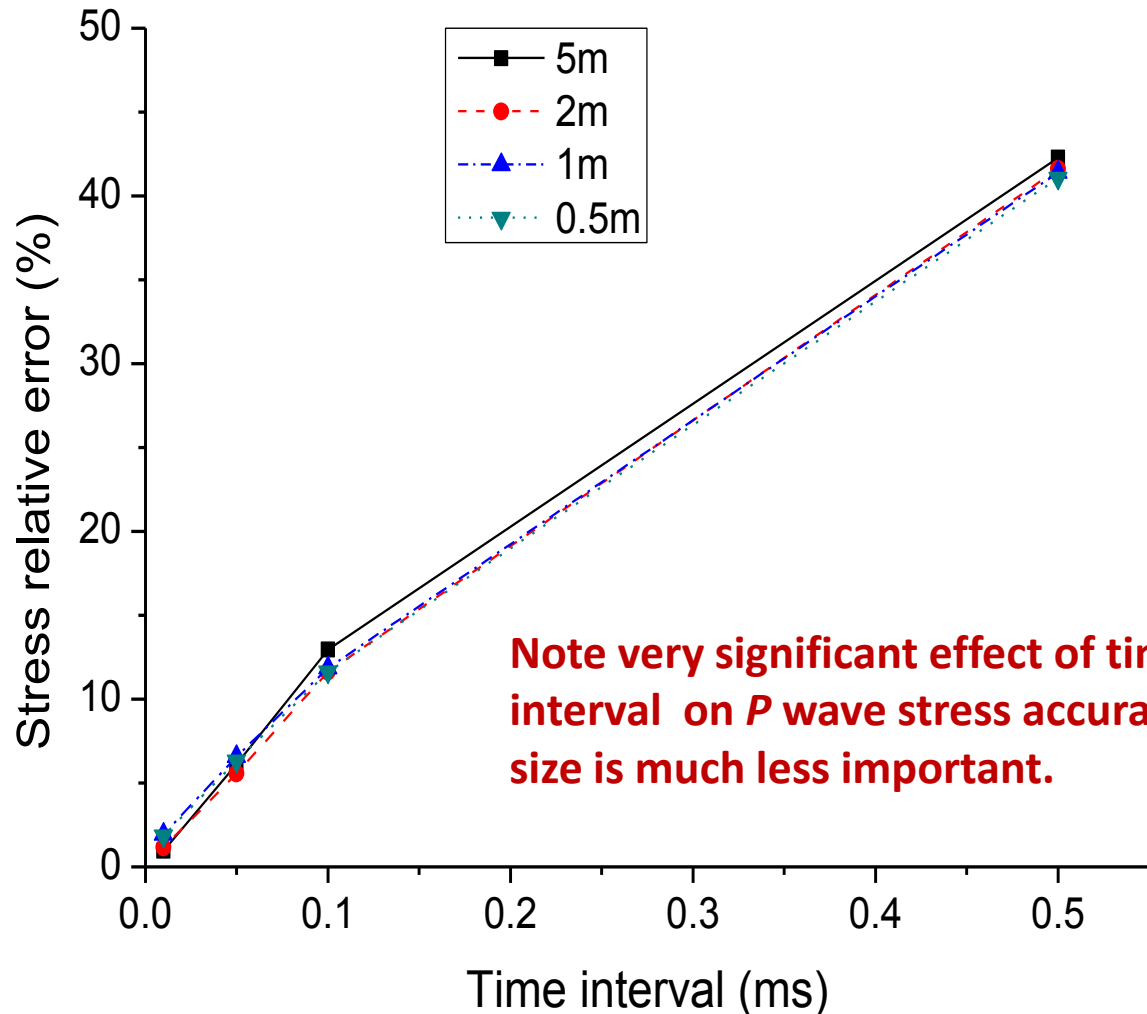
Input parameters for block and joint materials



Time interval effect on the accuracy of P wave stress

$$e = \frac{|A_1 - A_0|}{A_0} \times 100\%$$

where A_1 is the measured wave amplitude or calculated wave velocity at a reference measurement point in the model, and A_0 is the incident wave amplitude or analytical wave velocity at a given point.



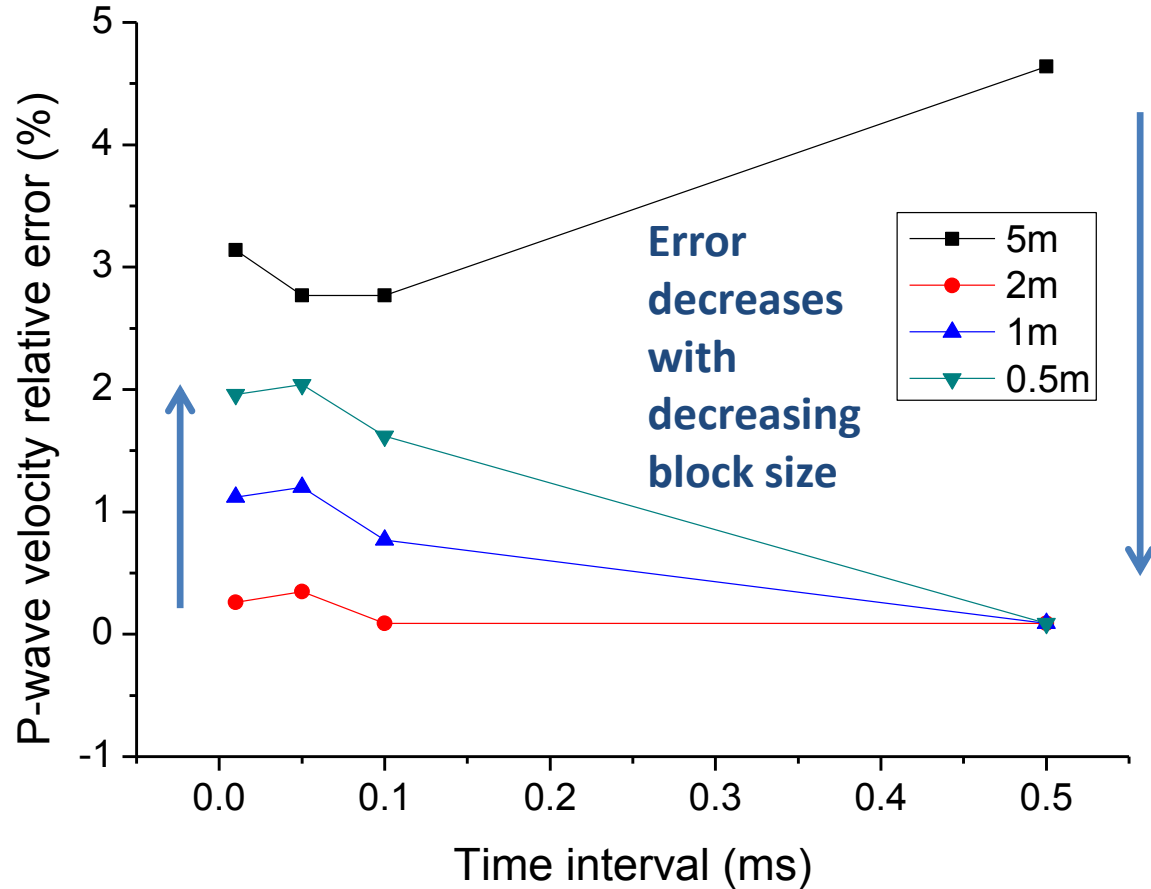


Time interval effect on the accuracy of *P* wave velocity

For the special case of a one dimensional bar (Kolsky, 1964):

$$V_p = \sqrt{\frac{E}{\rho_0}}$$

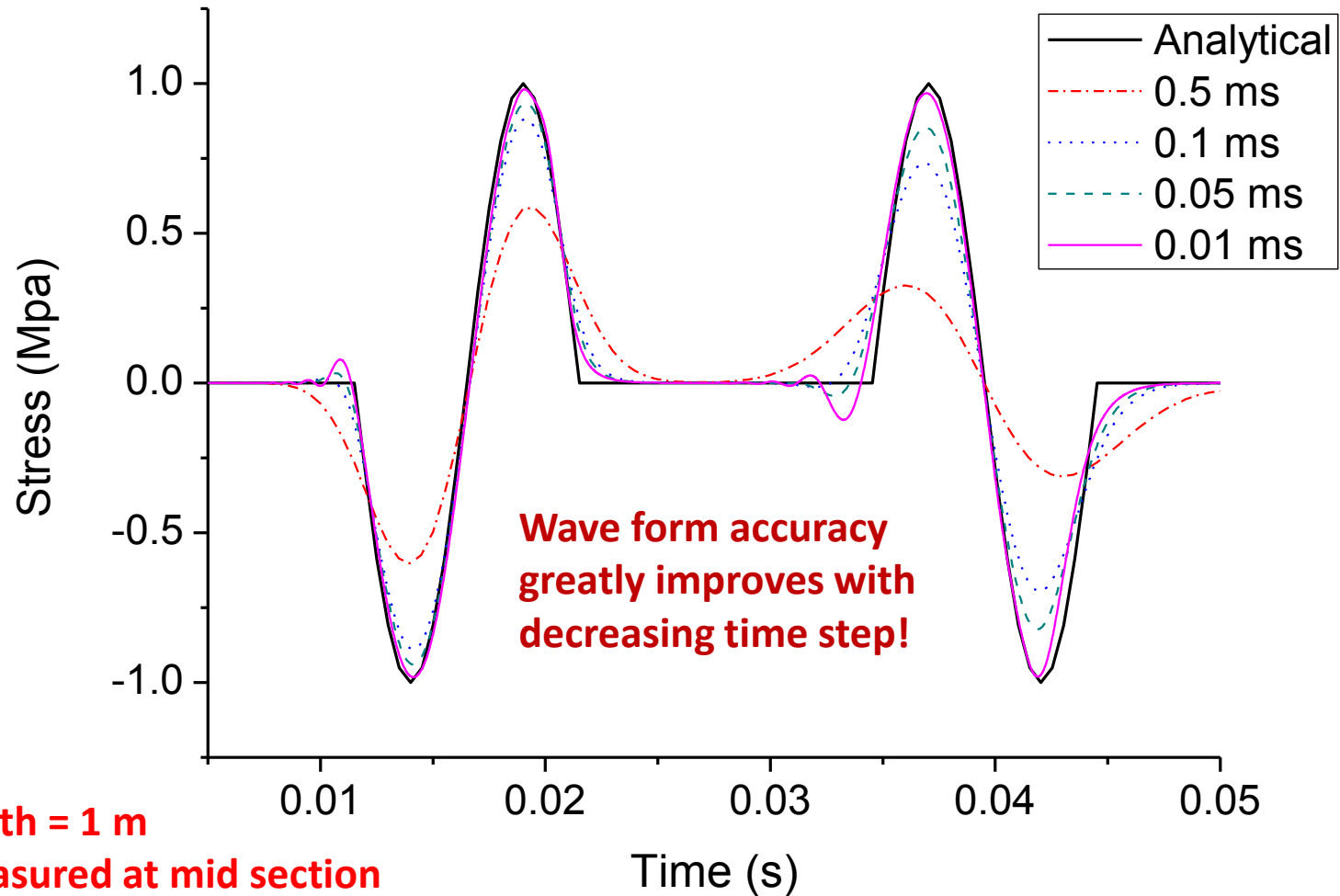
Error increases with decreasing block size



Note complicated block size effect on *P* wave velocity; time interval is much less important. There seems to be an optimal block size below which the error increases!



Time interval effect on waveform accuracy

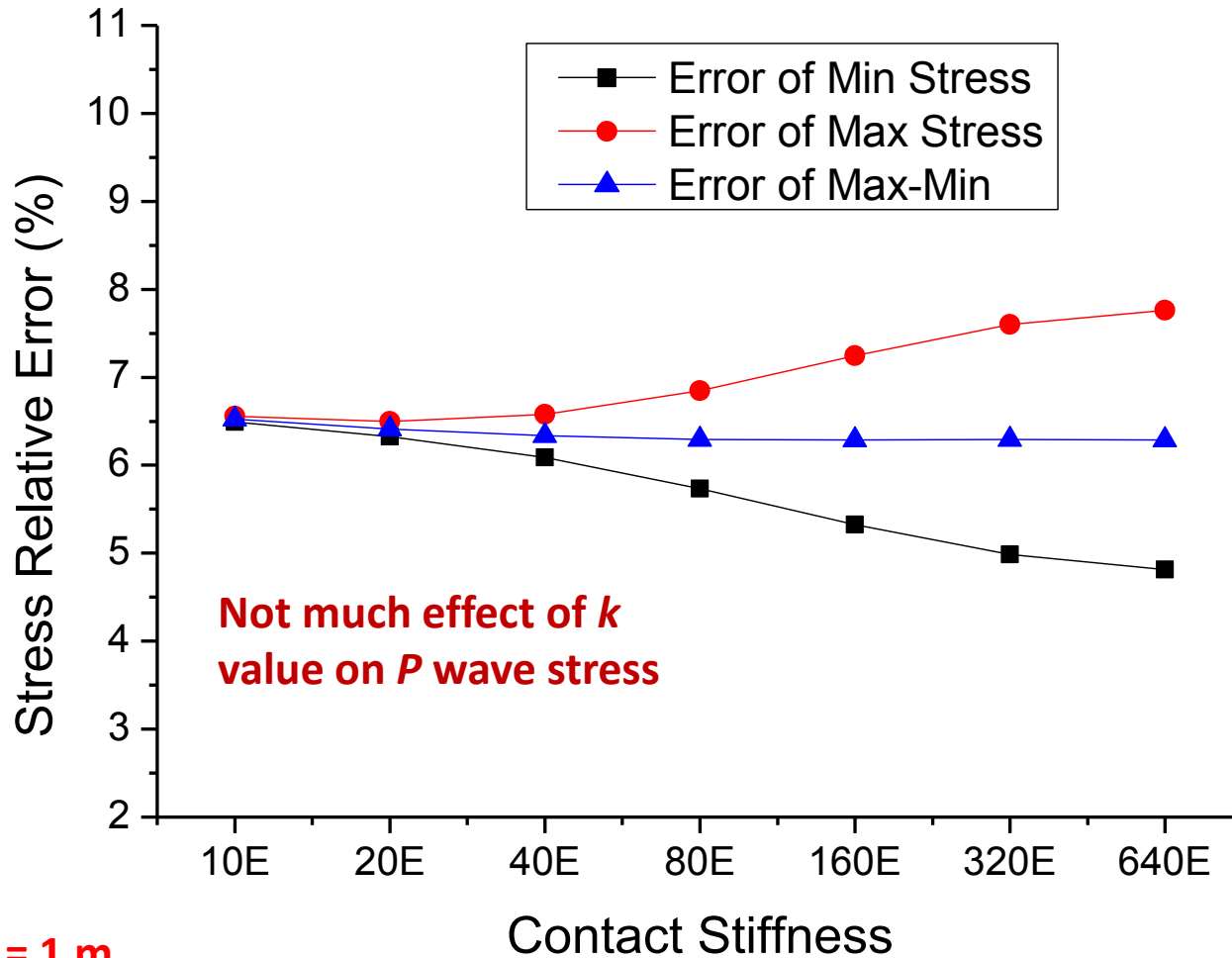


Block length = 1 m

Stress measured at mid section



Contact stiffness (k) effect on P wave stress accuracy

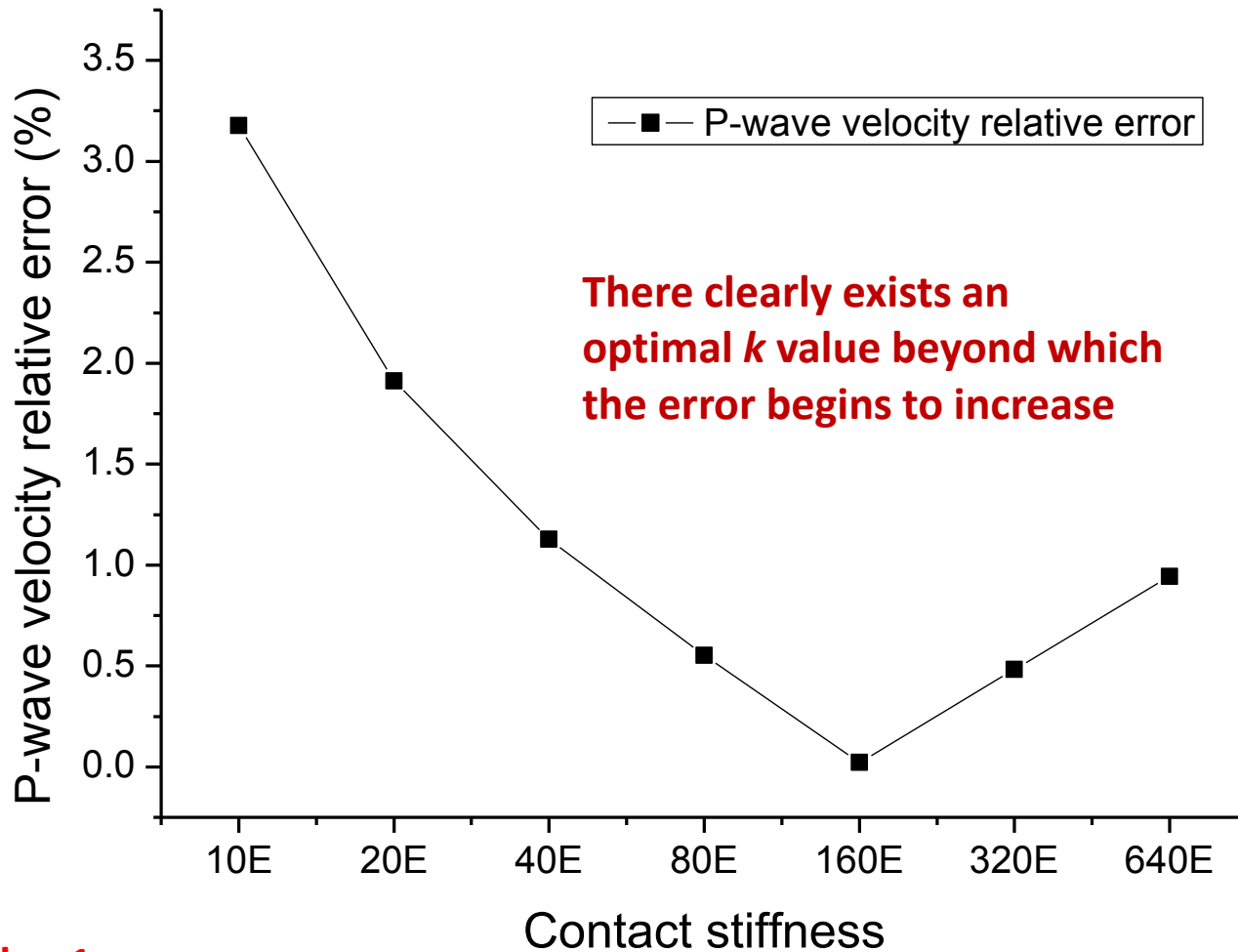


Block length = 1 m

Stress measured at mid section



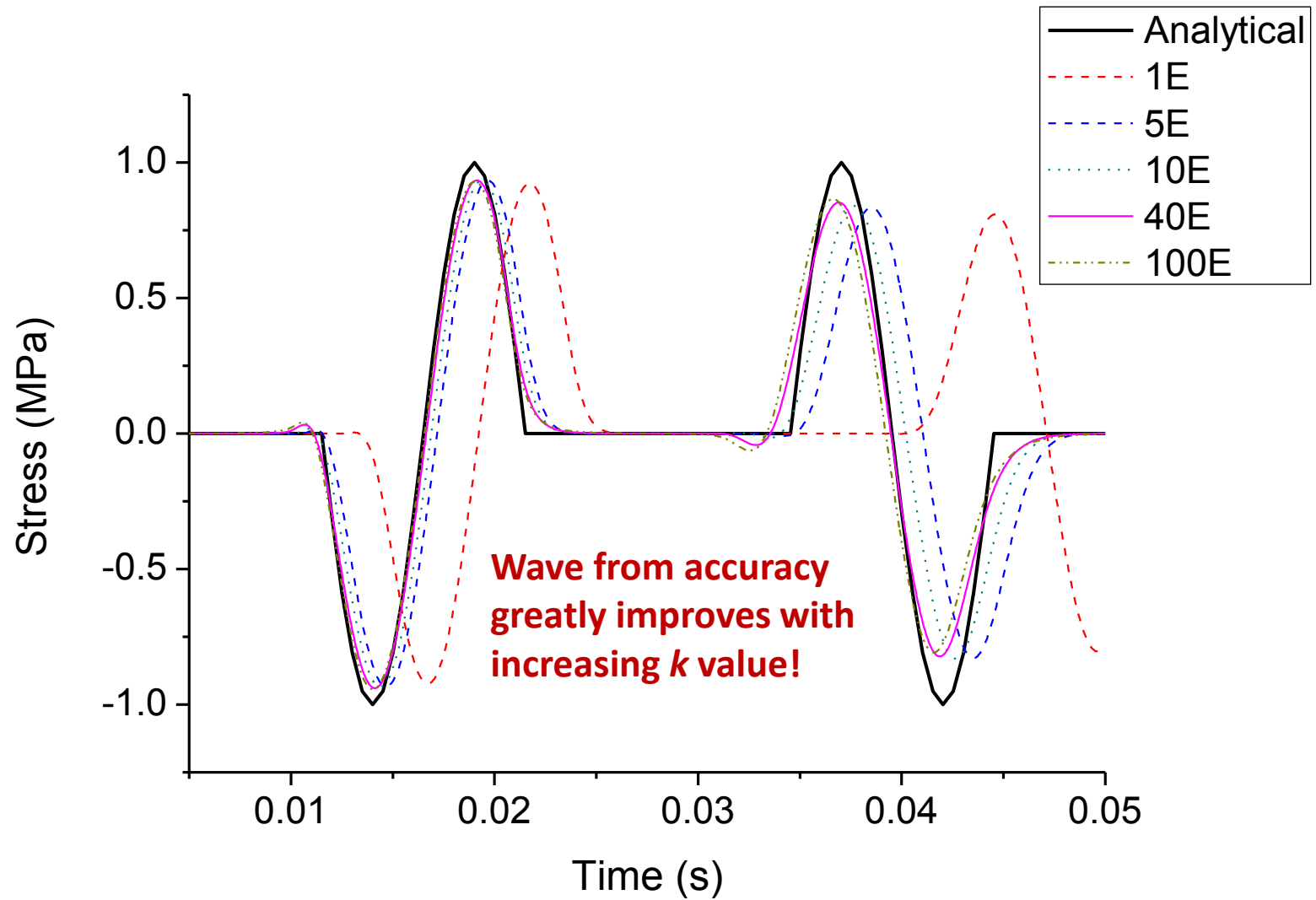
Contact stiffness (k) effect on P wave velocity accuracy



Block length = 1m



Contact stiffness (k) effect on waveform accuracy



Block length = 1m



Relationship between wavelength and block size

The relationship between element (block) side length (Δx) and wave length (λ), has a strong influence on numerical accuracy. In FEM the optimal ratio η should be smaller than 1/12 (0.083) where:

$$\eta = \frac{\Delta x}{\lambda}$$

In our simulations:

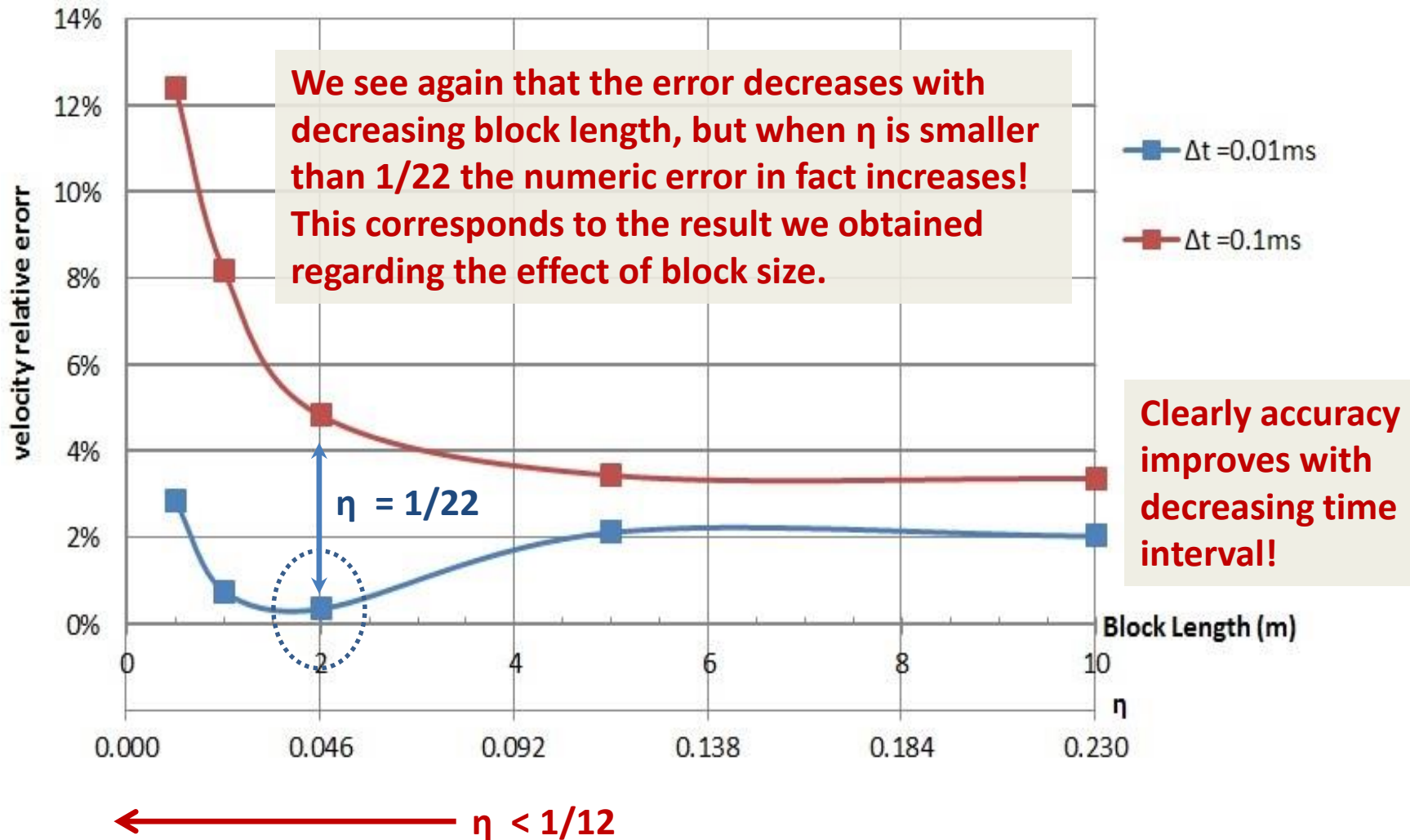
T (s)	0.01
v (m/s)	4343
λ (m)	43.43

We have performed a series of tests for various values of η and obtained the following results:

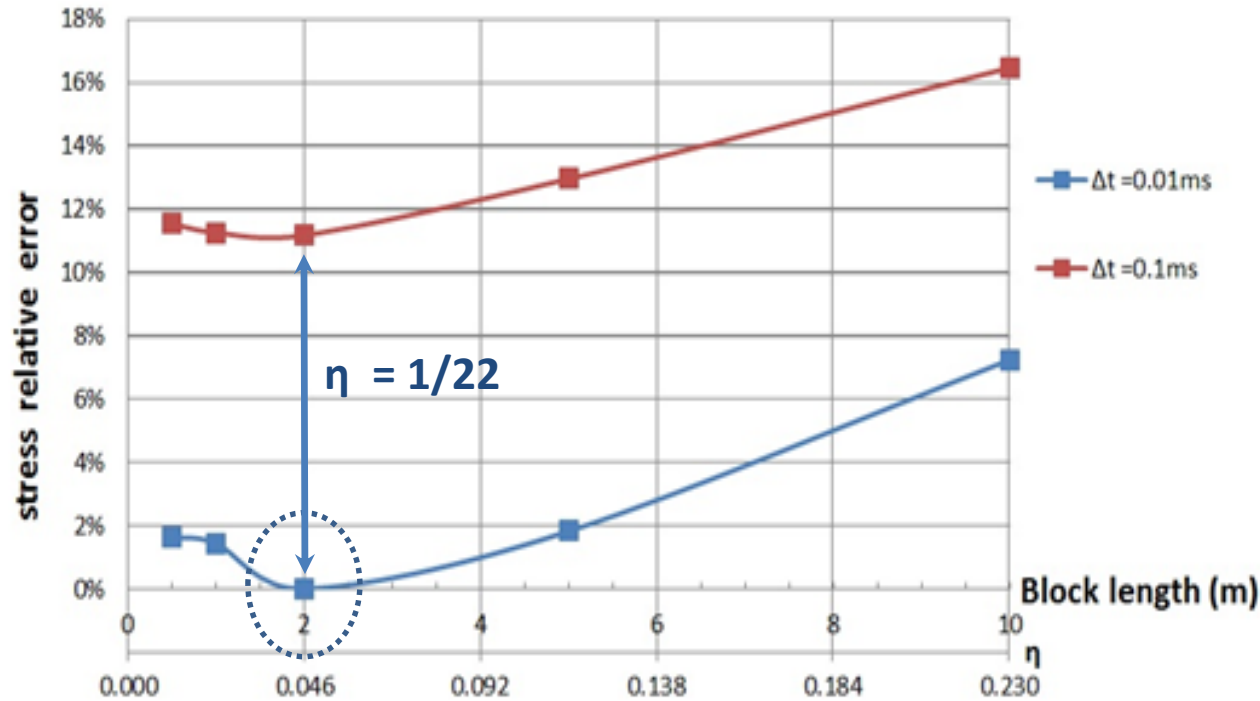
Δt (ms)	Block length (m)	0.5	1	2	5	10
	η ($\Delta x/\lambda$)	0.012	0.023	0.046	0.115	0.230
0.01	Velocity (m/s)	4219.16	4310.34	4359.20	4436.36	4432.43
	Error	2.87%	0.77%	0.36%	2.13%	2.04%
0.1	Velocity (m/s)	4884.24	4699.91	4553.73	4493.57	4490.35
	Error	12%	8%	5%	3%	3%



Influence of η on velocity accuracy



Influence of η on stress accuracy



Great improvement in stress accuracy with decreasing block length down to a minimum at $\eta = 1/22$ below which the error increases for both time intervals studied.

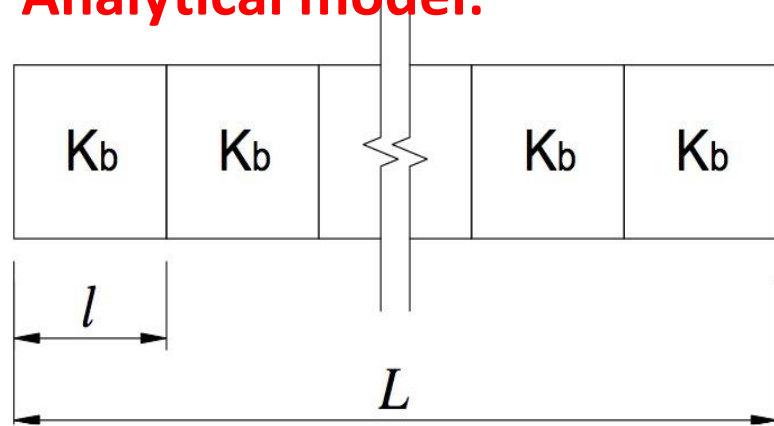
Very significant accuracy improvement with decreasing time interval.

Δt (ms)	block length (m)	0.5	1	2	5	10
	η ($\Delta x/\lambda$)	0.012	0.023	0.046	0.115	0.230
0.01	Amplitude (KPa)	983.6	985.4	999.8	981.6	927.5
	error	1.6%	1.5%	0.0%	1.8%	7.2%
0.1	Amplitude (KPa)	884.6	887.3	888.2	870.3	835.3
	error	11.5%	11.3%	11.2%	13.0%	16.5%



The problem with adding joints artificially

Analytical model:



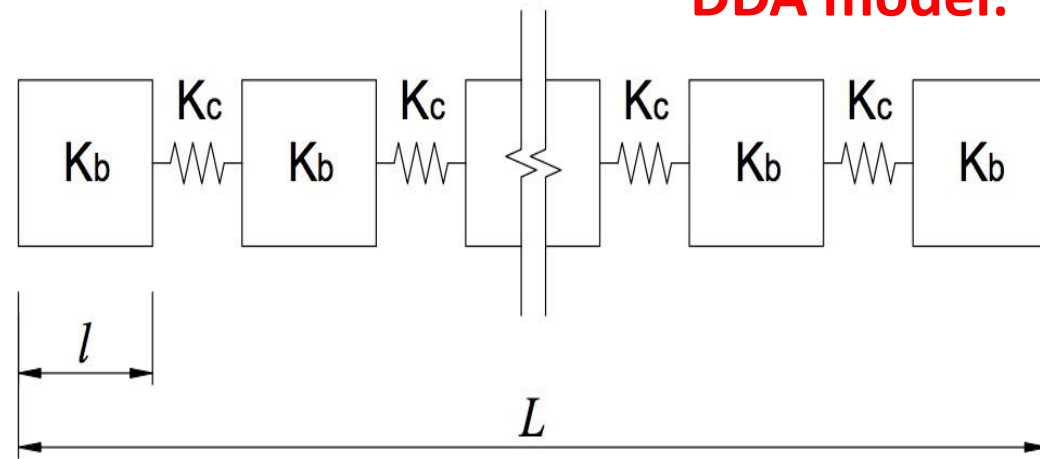
In the analytical model there is no additional stiffness from contact springs as in the DDA model, and the total stiffness of a block system of length L is:

$$K_L = \frac{K_b}{n_b}$$

where n_b is the number of blocks in specified length L .

Artificially decreasing the size of blocks down to a certain value may increase stress accuracy, but below a value of $\eta \approx 1/22$ errors both in stress and velocity will increase because of the inaccurate representation of the real stiffness of the system due the large number of contacts.

DDA model:



In the DDA model, the total stiffness of the block system in length L is:

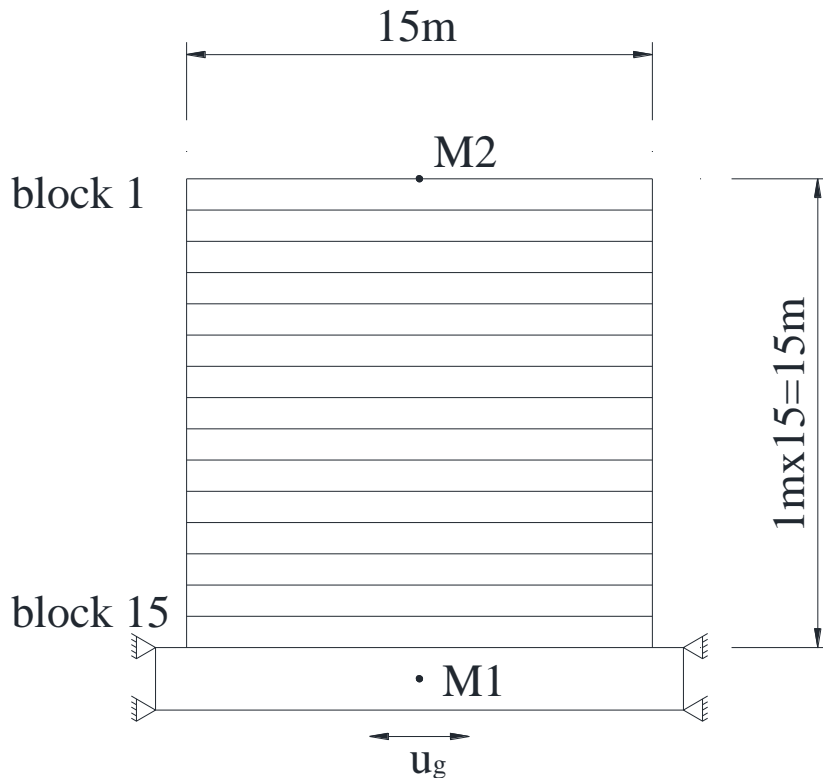
$$\hat{K}_L = \frac{1}{K_L} + \frac{n_c}{K_c}^{-1} < K_L$$

where n_c is the number of contact springs in specified length L .

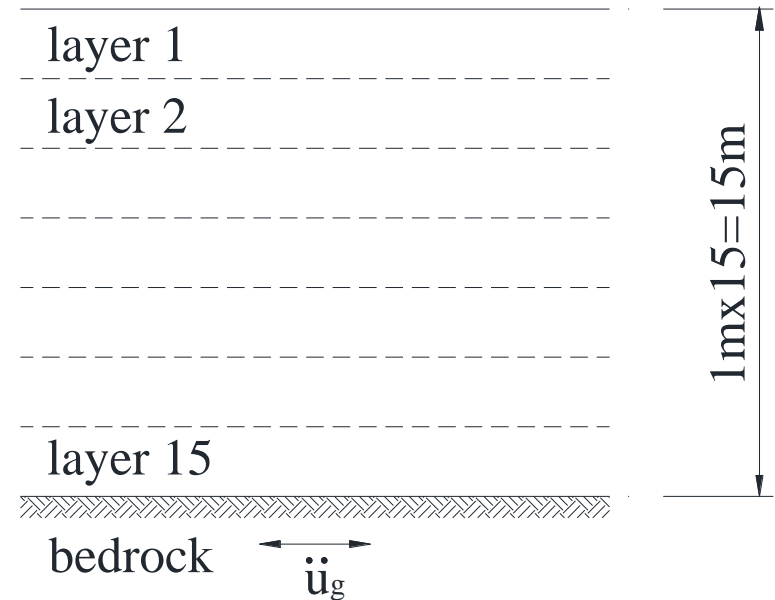


S wave propagation: DDA vs. SHAKE

DDA Model



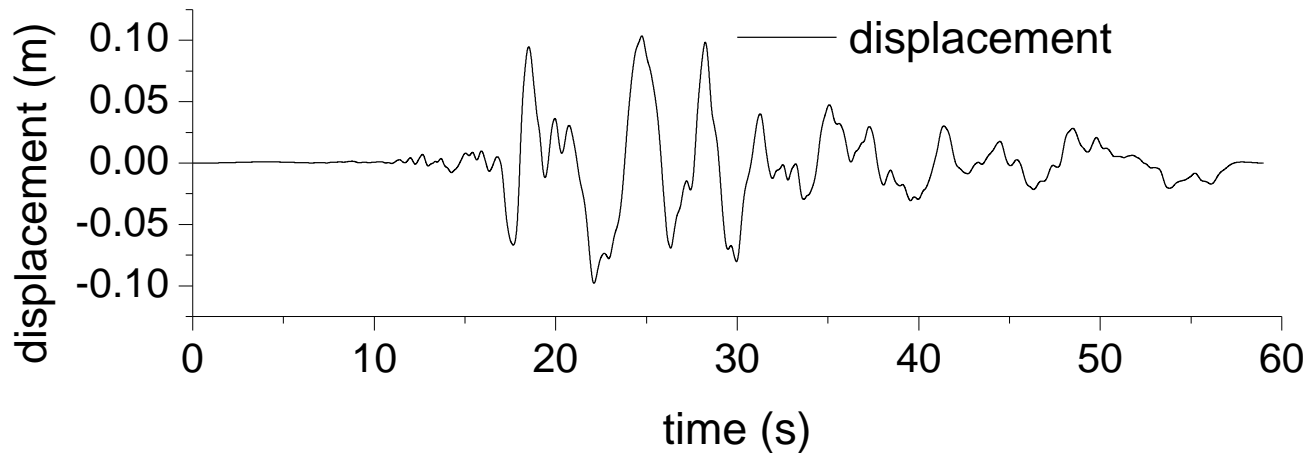
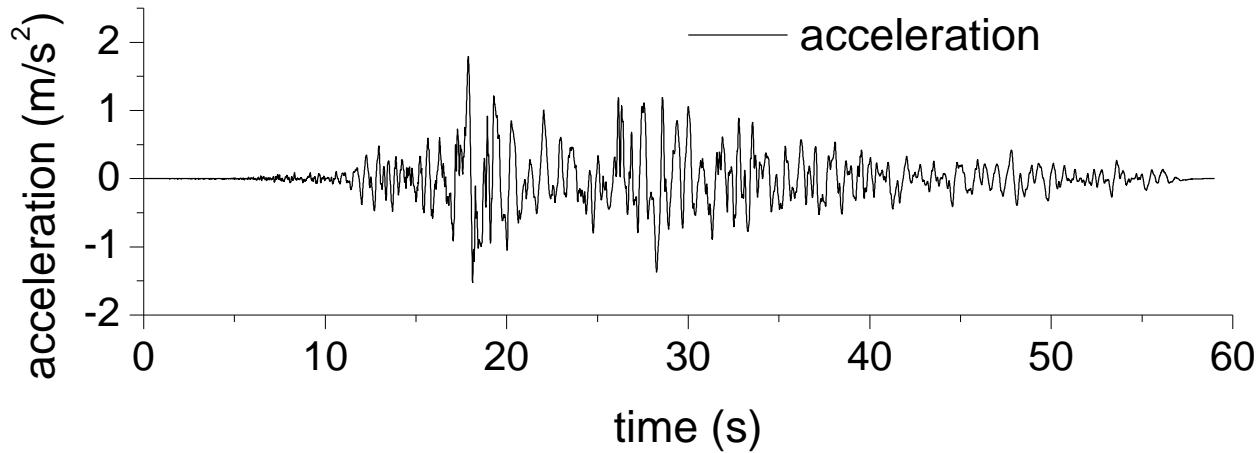
SHAKE model



Bao, Yagoda-Biran, and Hatzor, *Earthquake Engineering and Structural Dynamics* (in press)



Input Ground Motions

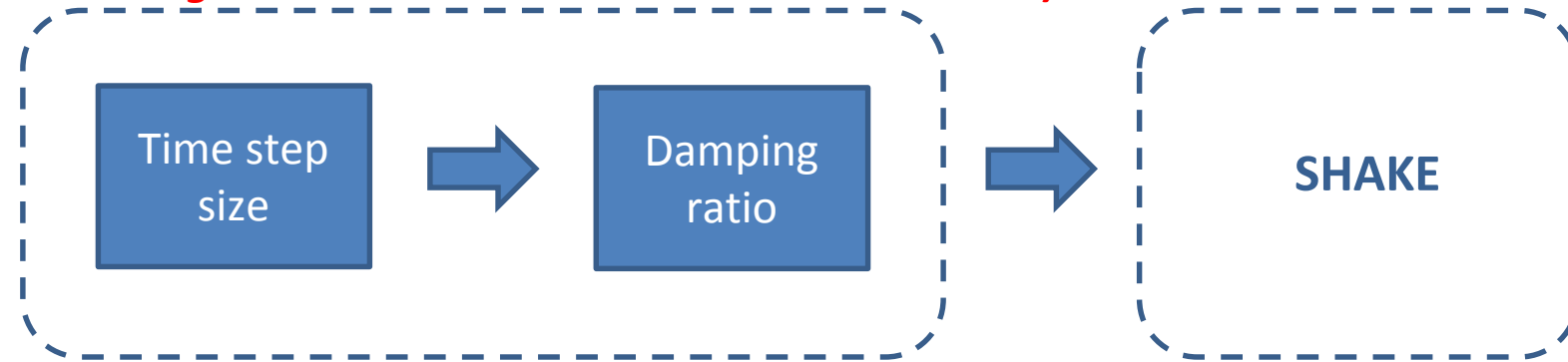


CHI-CHI 09/20/99, ALS, E (CWB): acceleration for SHAKE and displacement for DDA



Modeling Procedure

Damping ratio transfer from DDA into SHAKE utilizing DDA algorithmic damping (for details on the algorithmic in DDA See Doolin and Sitar 2004)



DDA

Modeled material parameters in layered model

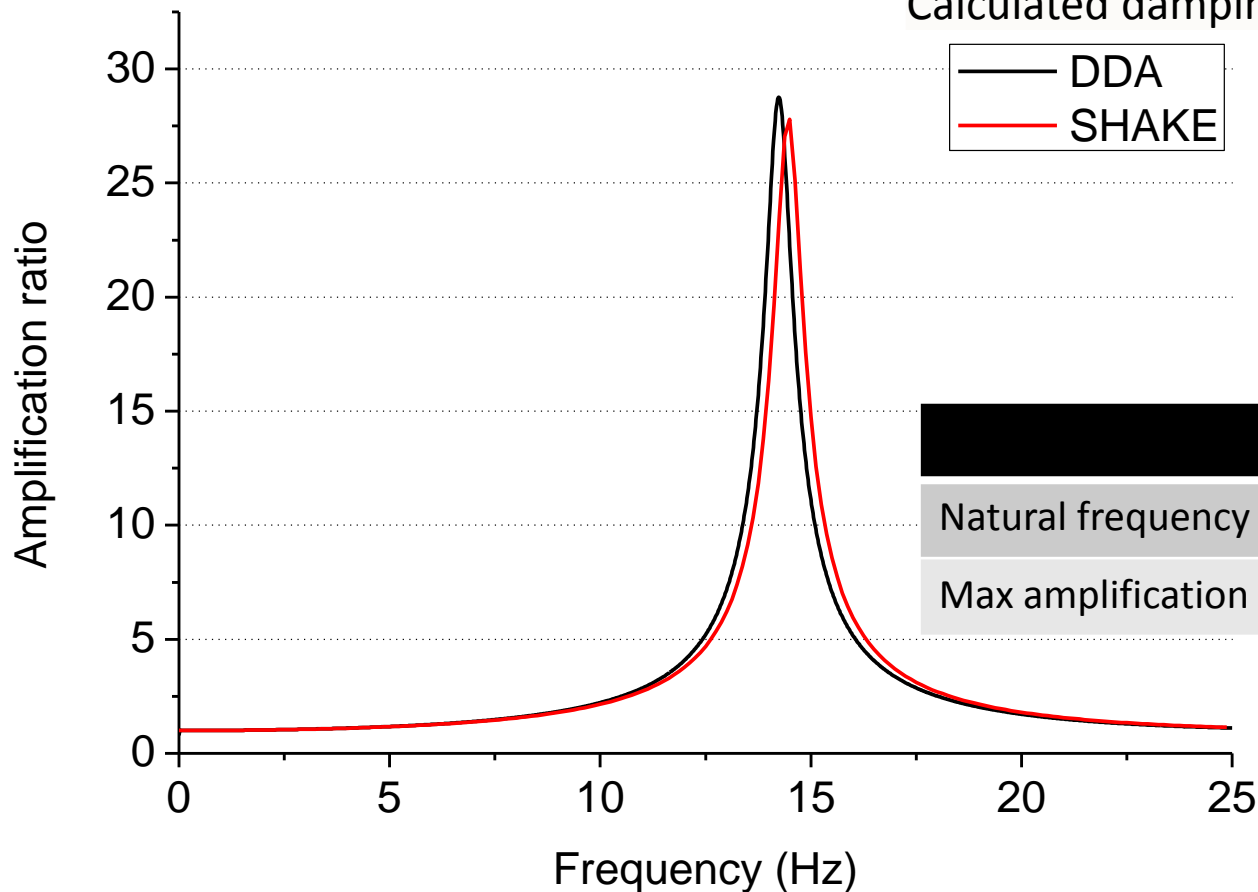
Layer/Block	Unit mass (kg/m ³)	Young's Modulus (GPa)	Shear Modulus (GPa)	Poisson ratio
1-3	2403	4.5	1.8	0.25
4-6	2162	4.1	1.64	0.25
7-9	2243	4.2	1.68	0.25
10-12	2483	4.0	1.6	0.25
13-15	2643	4.8	1.92	0.25



Spectral Amplification Ratio

DDA numerical control parameters

time step size (s):	0.001
Total steps:	60000
Spring stiffness (N/m):	1.50E+12
Calculated damping ratio:	2.3%



	DDA	SHAKE
Natural frequency (Hz)	14.23	14.50
Max amplification	28.76	27.79



2D Site Response: DDA vs. Field Test



“Static” Push and Release at top column →

“Dynamic” blow with sledgehammer at column base ↓



Bao, Yagoda-Biran, and Hatzor, *Earthquake Engineering and Structural Dynamics* (in press)

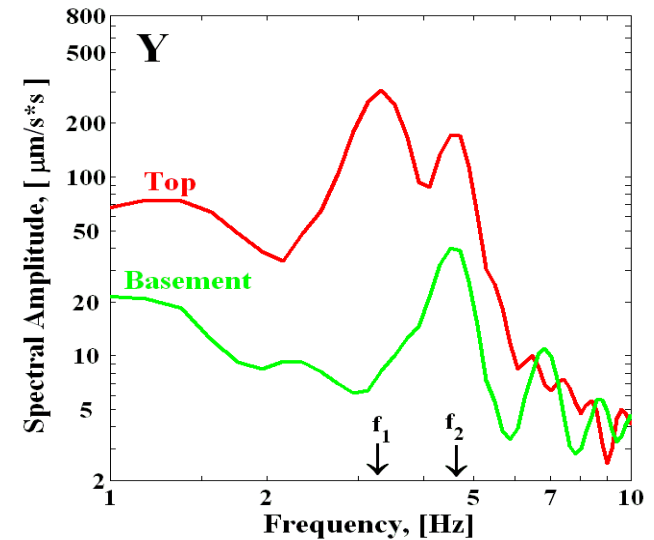
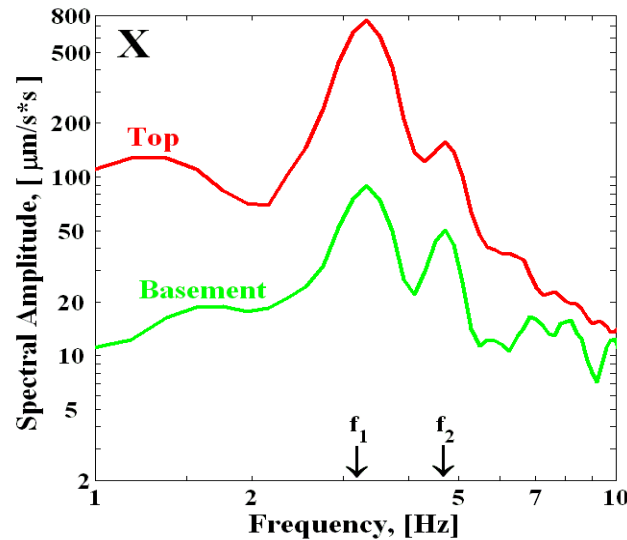
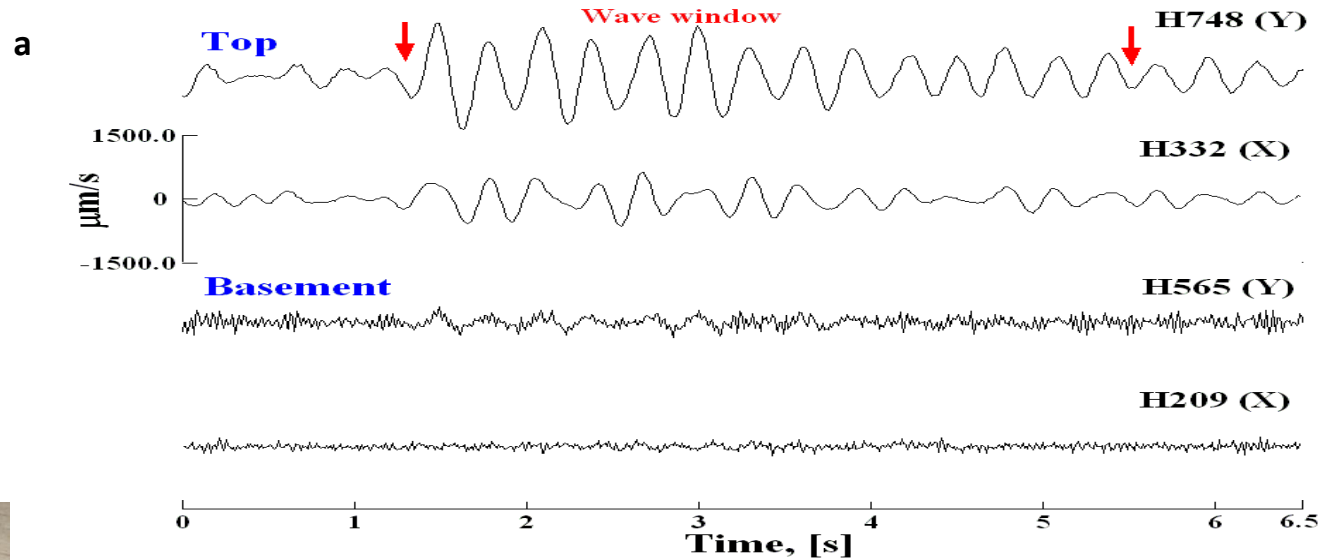


Results of Geophysical Field Measurements

Typical vibrations of the Column top and base in the X and Y directions due to force excitation in the Y direction by horizontal stroke of sledgehammer at the base of the Column



The corresponding Fourier amplitude spectra for the top and base of the Column.





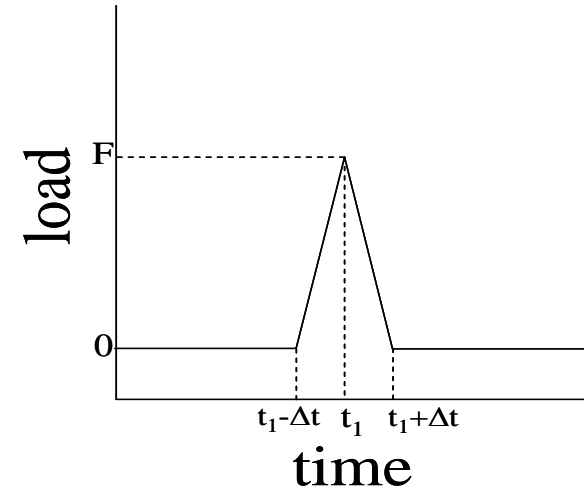
The DDA model of a multi-drum column



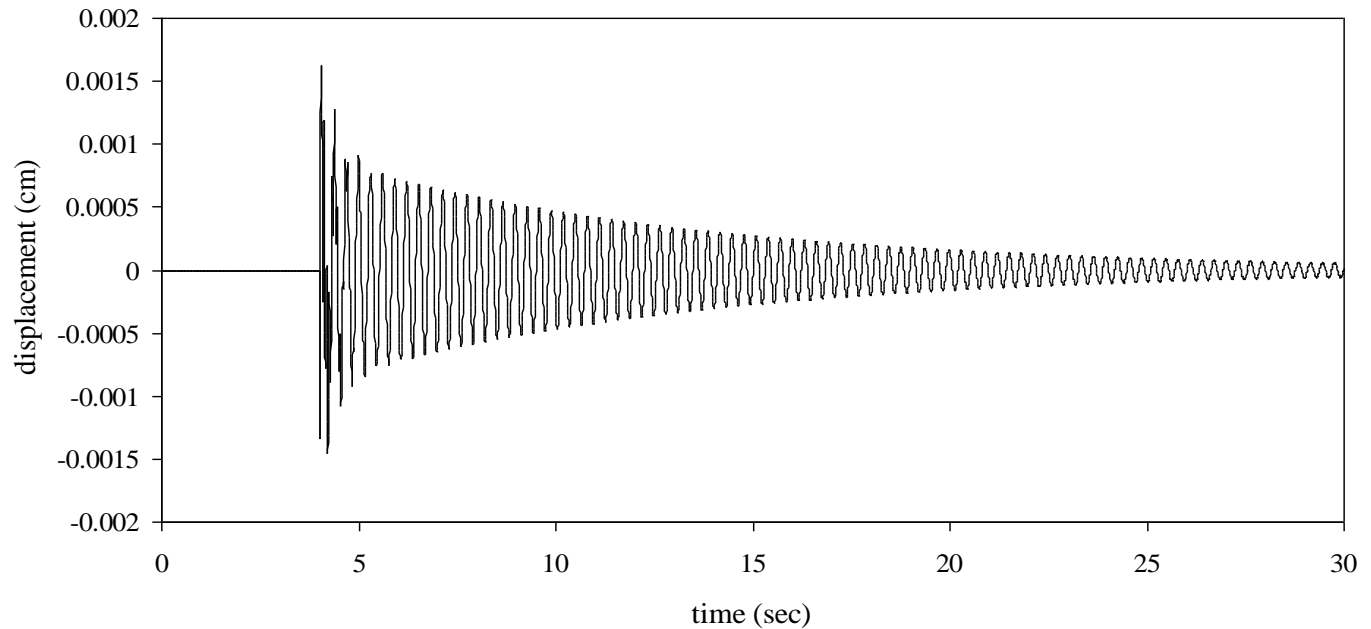
Parameter	Value
Young's modulus	17 GPa
Poisson's ratio	0.22
Interface Friction	30°
Density	2250 kg/m ³
Time step	0.01-0.001 sec.
Displacement ratio	0.01 – 0.001
k (penalty value)	2x10 ⁷ - 2x10 ⁷ N/m



DDA response to dynamic pulse of 10,000 N

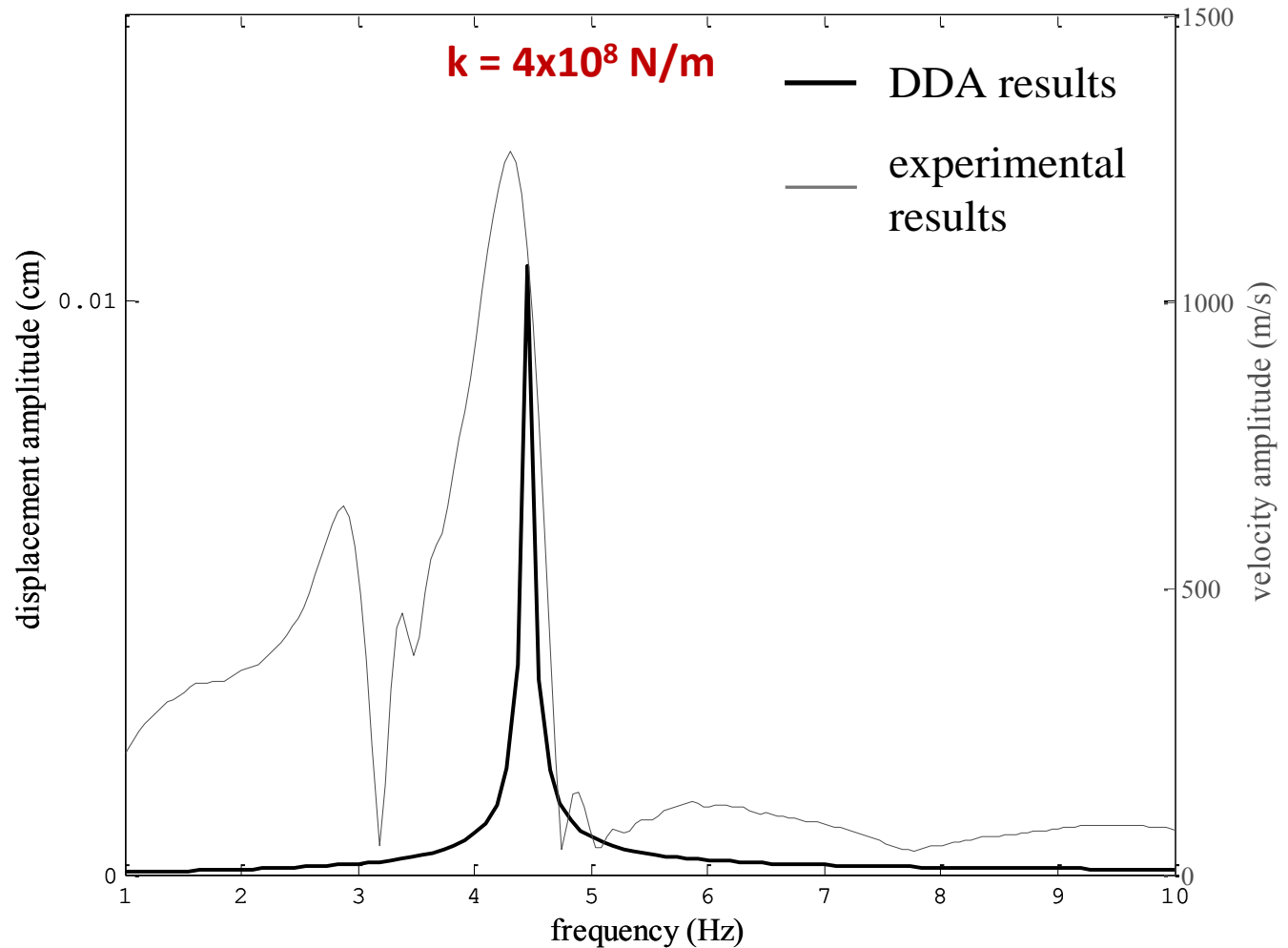
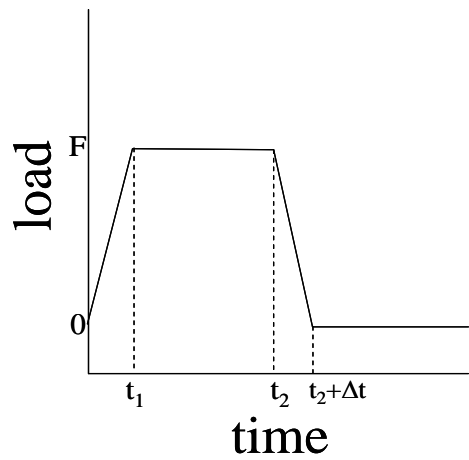


Dynamic response of uppermost block in time domain



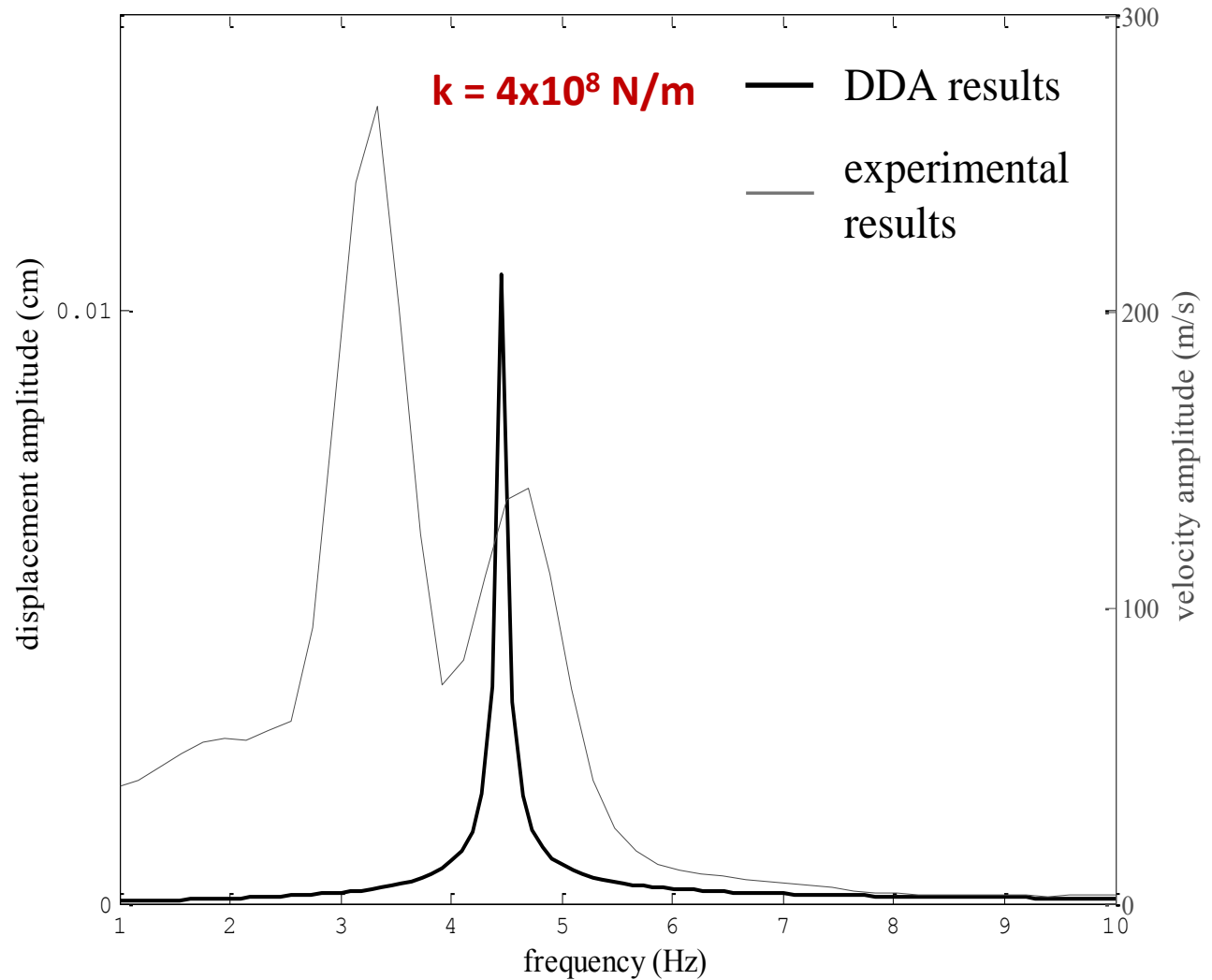
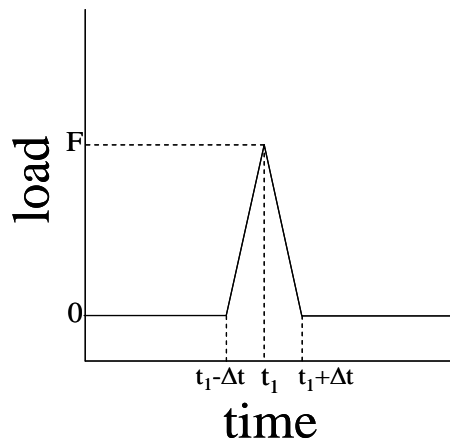


Top column response to static push: DDA vs. Geophysical survey





Top column response to dynamic blow: DDA vs. Geophysical survey





DDA sensitivity of resonance frequency to penalty value k

FFT of uppermost
block
displacement

