ICOLD

INTERNATIONAL COMMISSION ON LARGE DAMS

ICOLD COMMITTEE ON COMPUTATIONAL ASPECTS OF ANALYSIS AND DESIGN OF DAMS

15th INTERNATIONAL BENCHMARK WORKSHOP ON NUMERICAL ANALYSIS OF DAMS

Theme A - Formulation

SEISMIC ANALYSIS OF PINE FLAT CONCRETE DAM

9 September 2019, Milan, Italy

Evaluation of Seismic Wave Propagation in the Analysis of Concrete Dams

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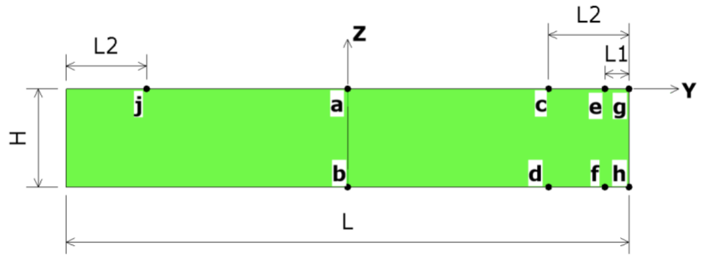
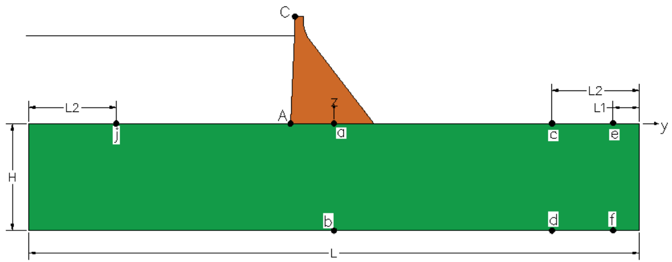
Introduction

- The primary focus of this paper is to examine some basic problems in seismic wave propagation that can arise when using reduced-domain models of a semi-infinite medium.
- We explore the use of two finite element codes, DIANA FEA and LS-DYNA to model seismic wave propagations in an elastic medium and we evaluate their accuracy where the answer is known a priori.
- This presentation is based on the results for two benchmark study Cases B and C using the impulsive excitation signal.





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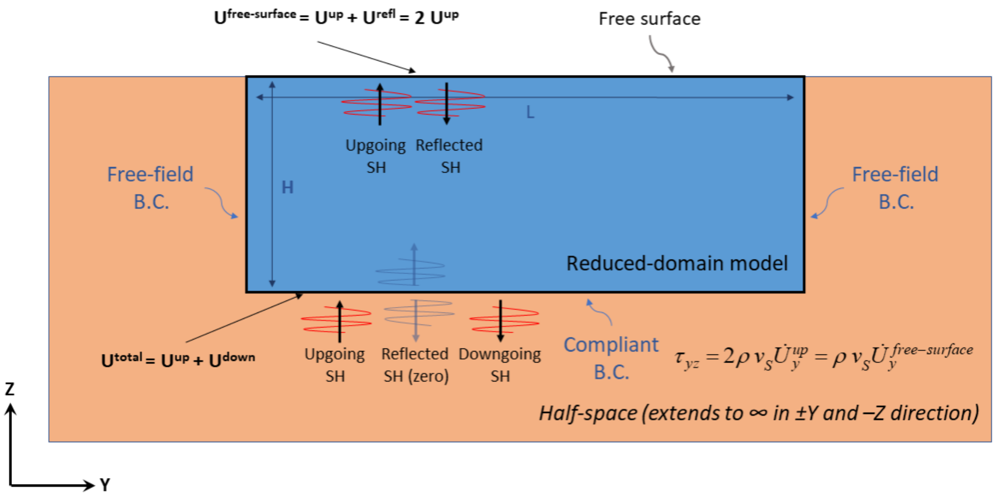
Semi-Infinite Medium vs. Reduced-Domain Model

- The reduced-domain model must adequately represent elastic wave propagation in a semi-infinite half-space.
- Boundary conditions are needed for the reduced-domain model to keep the motions at the side boundaries equivalent to what they would be in the semi-infinite medium, and to prevent internal reflections.



Evaluation conducted using 4 models:

(i) DIANA with <u>non-reflecting boundary</u> condition;

(ii) LS-DYNA with "<u>Boundary-Non-Reflecting</u>" conditions and an augmented input record re-sampled at 1/100th of the interval of the normal input record (time step 0.00001 s);

(iii) DIANA with a preliminary implementation of the <u>free-field boundary condition</u>; and

(iv) LS-DYNA with "<u>Boundary-Non-Reflecting</u>" conditions and a normal input record (time step = 0.001 s).

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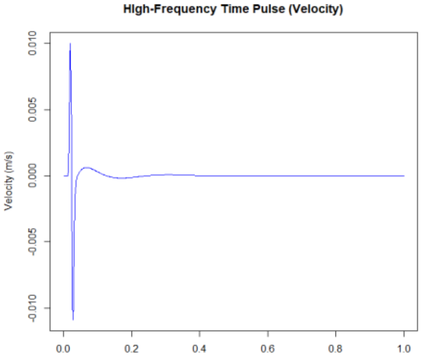
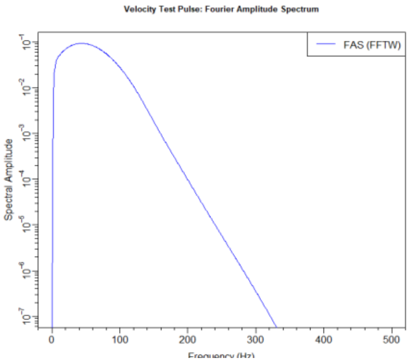
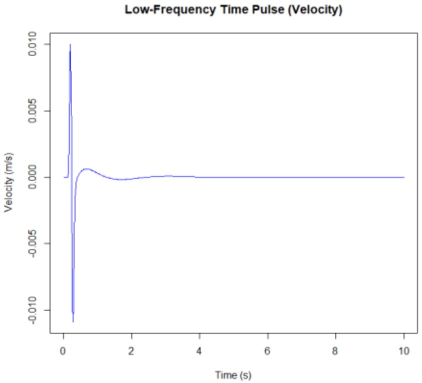
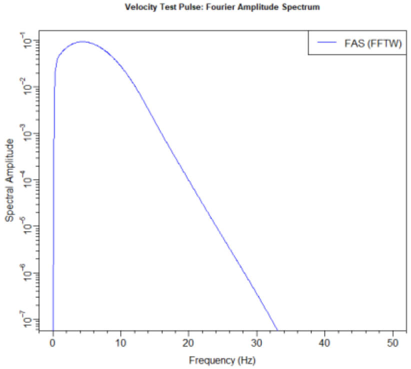
Impulsive Excitation

High and low frequency pulse









Impulse	Δt (sec.)	$F_{Nyquist}$ (Hz)	F_N (Hz)	F_{lo} (Hz)	F_{hi} (Hz)	Impulse Amplitude (m/s)	Record Duration (sec.)	Zero-pad (samp.)
Low Frequency	0.01	50	4.0	0.5	8.0	0.01	20	10
High Frequency	0.001	500	40	5	80	0.01	2.0	10

Misfit measure of computed vs. theoretical waveforms

Scale-*dependent* measure over the window $[t_1, t_2]$ is

$$mse^2 = \frac{1}{(t_2 - t_1 + 1)} \sum_{t_1}^{t_2} (v_t - \hat{v}_t)^2$$

Scale-*independent* normalized measure is

$$nmse = \left\{ mse^2 \Big/ \left[\left(\bar{v}_t - \bar{\hat{v}}_t \right)^2 + \sigma_v^2 + \sigma_{\hat{v}}^2 \right] \right\}^{1/2}$$

where $\bar{v}_t$ and $\bar{\hat{v}}_t$ are the means of the computed and theoretical time histories and σ_v^2 and $\sigma_{\hat{v}}^2$ are their variances

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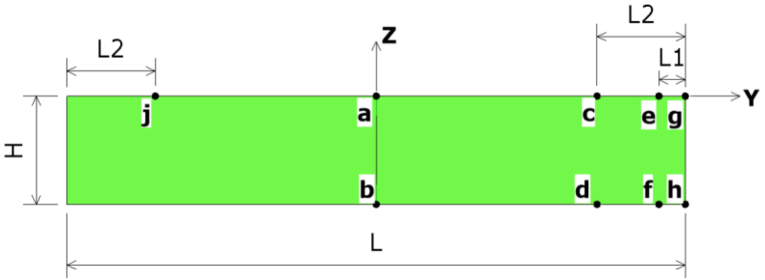
Case B - Foundation Block – High Frequency Pulse

Results at the foundation surface: **a, c, e, g**

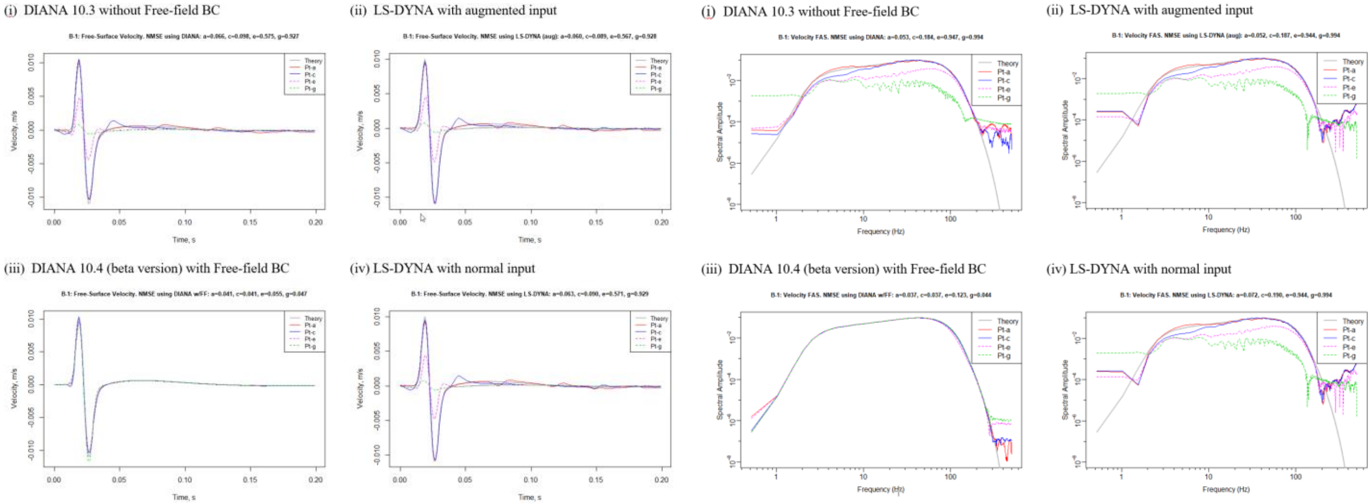


nmse – velocity

	a	*c*	*e*	*g*
(i)	0.066	0.098	0.575	0.927
(ii)	0.060	0.089	0.567	0.928
(iii)	0.041	0.041	0.055	0.047
(iv)	0.063	0.090	0.571	0.929

nmse – spectra

	a	*c*	*e*	*g*
(i)	0.053	0.184	0.947	0.994
(ii)	0.052	0.187	0.944	0.994
(iii)	0.037	0.037	0.123	0.044
(iv)	0.072	0.190	0.944	0.994



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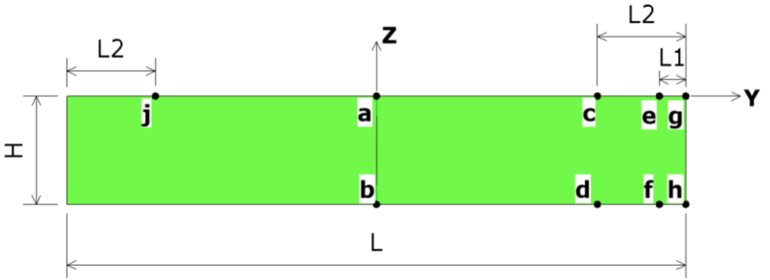
Case B - Foundation Block – Low Frequency Pulse

Results at the foundation surface: **a, c, e, g**



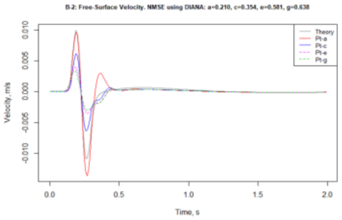
nmse – velocity

	a	*c*	*e*	*g*
(i)	0.210	0.354	0.581	0.638
(ii)	0.206	0.362	0.586	0.642
(iii)	0.008	0.008	0.008	0.009
(iv)	0.023	0.367	0.589	0.644

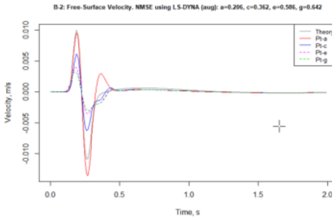
nmse – spectra

	a	*c*	*e*	*g*
(i)	0.430	0.816	0.924	0.939
(ii)	0.413	0.820	0.926	0.940
(iii)	0.022	0.022	0.022	0.024
(iv)	0.400	0.822	0.926	0.940

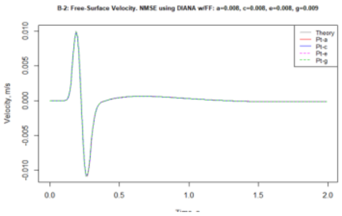
(i) DIANA without Free-field BC



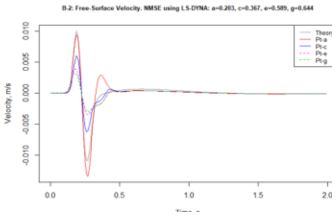
(ii) LS-DYNA with augmented input



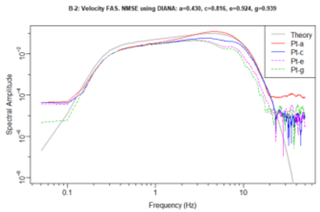
(iii) DIANA with Free-field BC



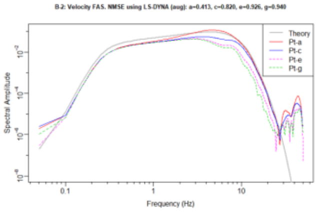
(iv) LS-DYNA with normal input



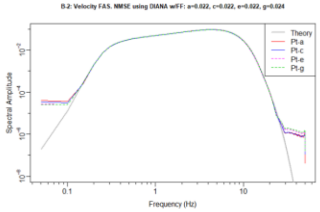
(i) DIANA 10.3 without Free-field BC



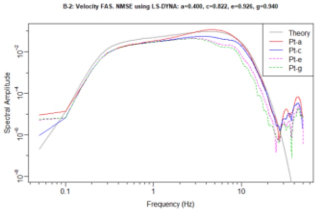
(ii) LS-DYNA with augmented input



(iii) DIANA 10.4 (beta version) with Free-field BC



(iv) LS-DYNA with normal input



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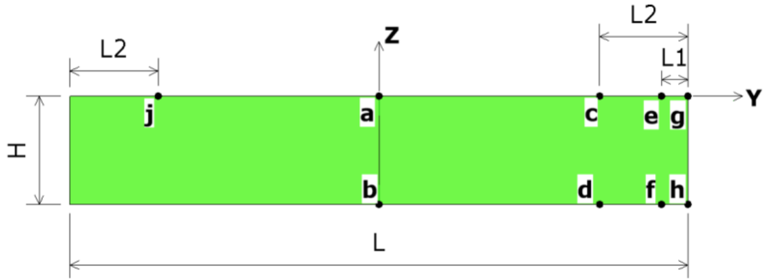
Case B - Foundation Block – High Frequency Pulse

Results at the foundation base: **b, d, f, h**



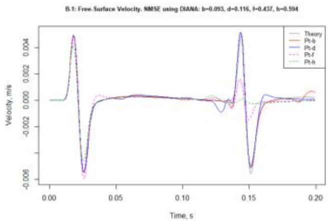
nmse – velocity

	b	*d*	*f*	*h*
(i)	0.093	0.116	0.437	0.594
(ii)	0.071	0.111	0.418	0.603
(iii)	0.075	0.075	0.072	0.105
(iv)	0.073	0.112	0.421	0.605

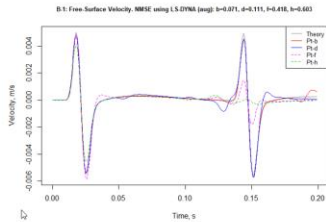
nmse – spectra

	b	*d*	*f*	*h*
(i)	0.043	0.151	0.611	0.823
(ii)	0.079	0.154	0.628	0.830
(iii)	0.027	0.026	0.124	0.038
(iv)	0.079	0.154	0.628	0.830

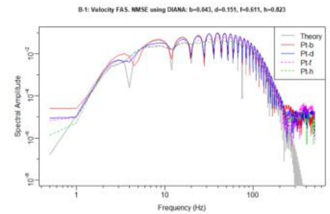
(i) DIANA 10.3 without Free-field BC



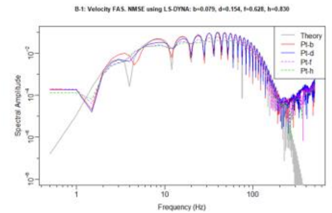
(ii) LS-DYNA with augmented input



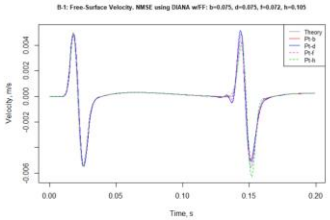
(a) DIANA 10.3 without Free-field BC



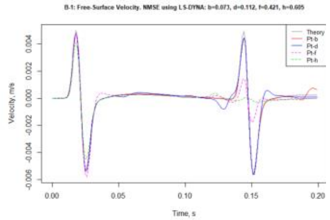
(b) LS-DYNA with augmented input



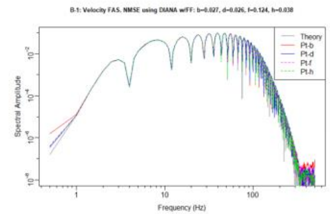
(iii) DIANA 10.4 (beta version) with Free-field BC



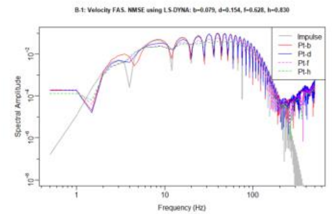
(iv) LS-DYNA with normal input



(c) DIANA 10.4 (beta version) with Free-field BC



(d) LS-DYNA with normal input



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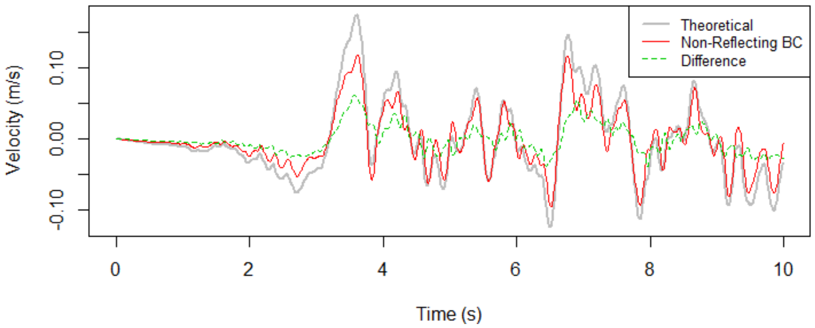
Case B - Foundation Block – Taft Earthquake

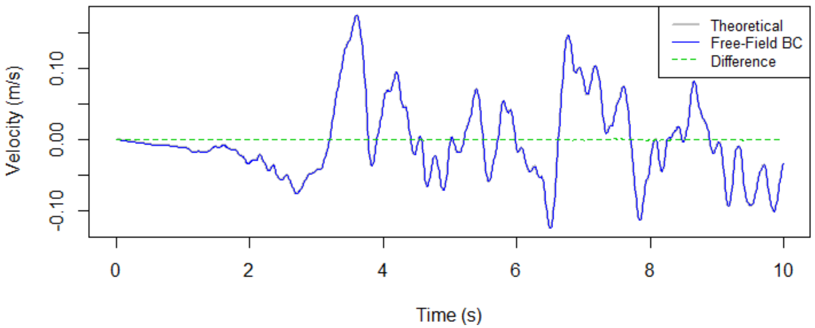
Results at the foundation top surface: Point **a**

- Very good agreement between theoretical solution & free-field BC results
- 30% lower peak velocities if only the non-reflecting BC is used

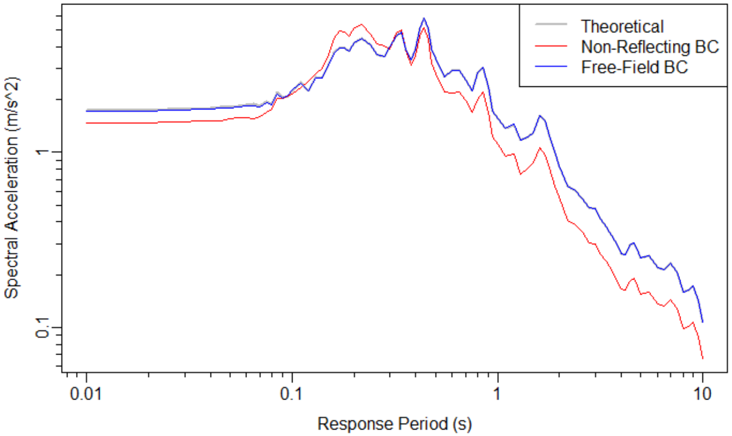
Velocities at Point a, Non-Reflecting BC: NMSE: 0.276

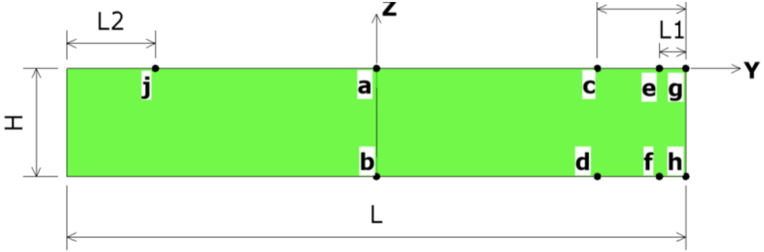


Velocities at Point a, Free-Field BC: NMSE: 0.004



Response Spectra at Point a. NMSE: Non-Reflecting BC=0.462, Free-Field BC=0.006





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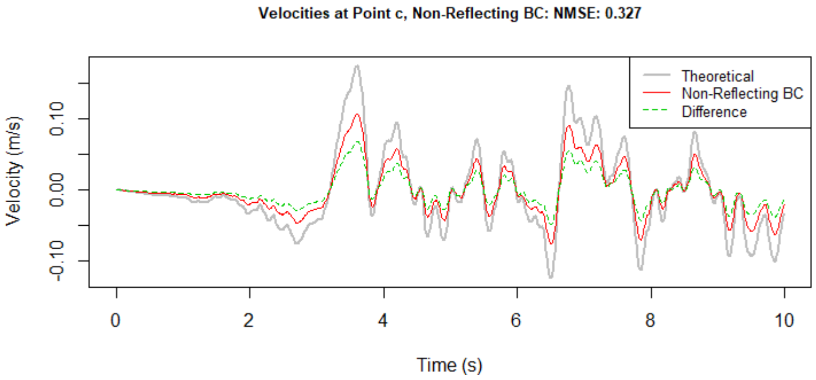
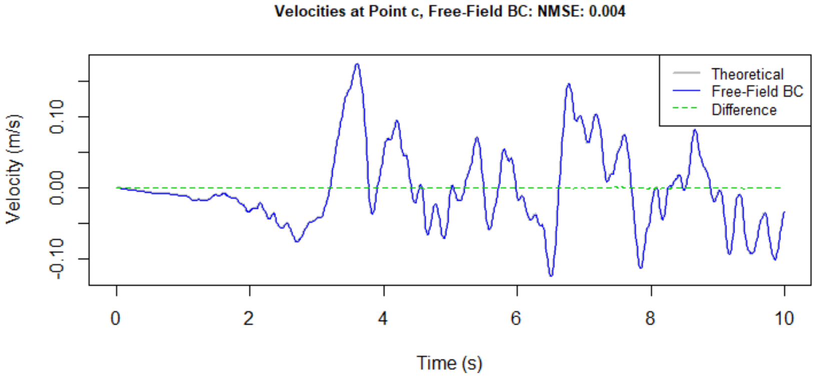
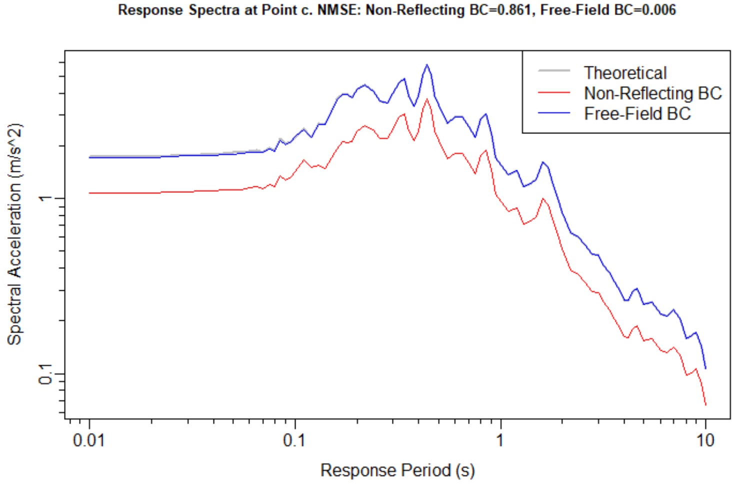
Case B - Foundation Block – Taft Earthquake

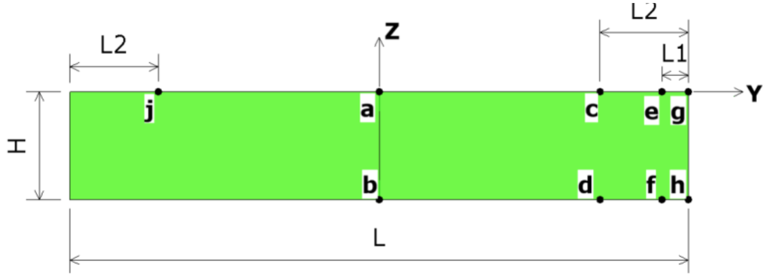
Results at the foundation top surface: Point **c**

- Very good agreement between theoretical solution & free-field BC results
- 40% lower peak velocities if only the non-reflecting BC is used









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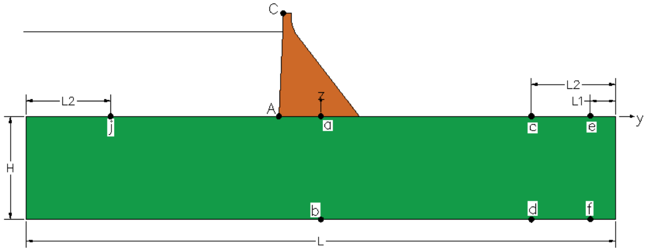
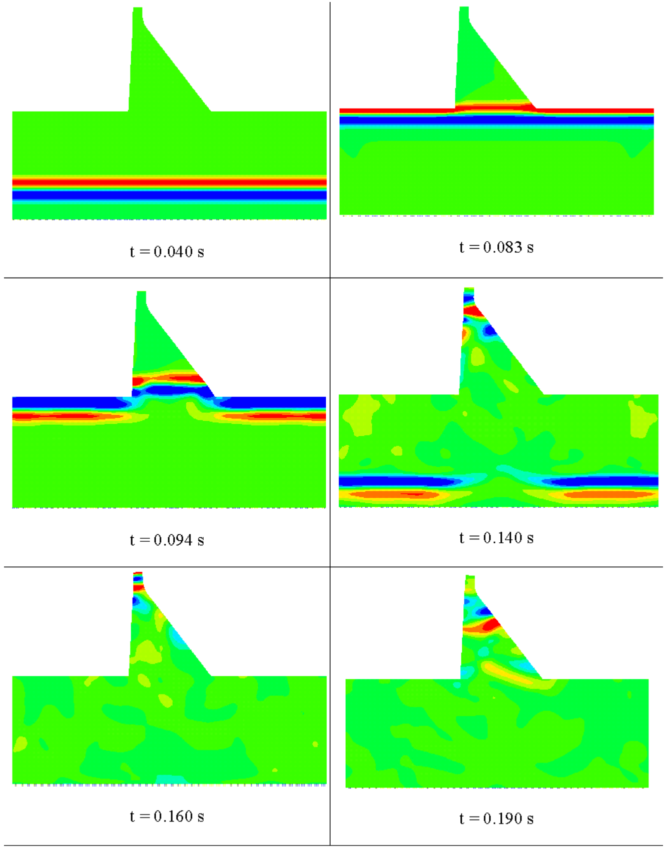
Foundation / Dam Model (Case C) Study

Illustration of a seismic wave propagation in a dam-foundation system:

- Uniform upgoing wave in the foundation
- Dam presence interrupts continuity of the wave
- A part of the wave reflects from the upper face of the foundation and a part of the wave propagates into the dam structure until it is reflected from the dam crest
- The disturbed wave starts to propagate down back to the foundation





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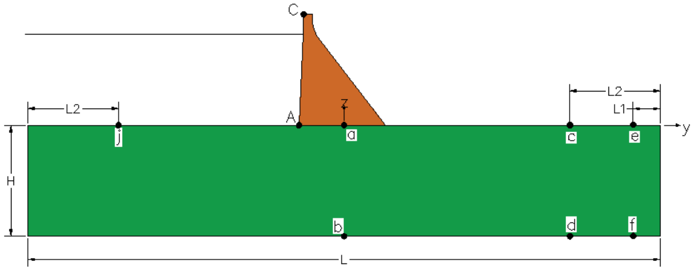
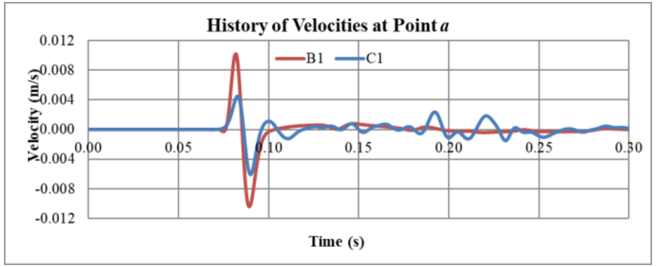
Comparison of Case B and Case C

Observations:

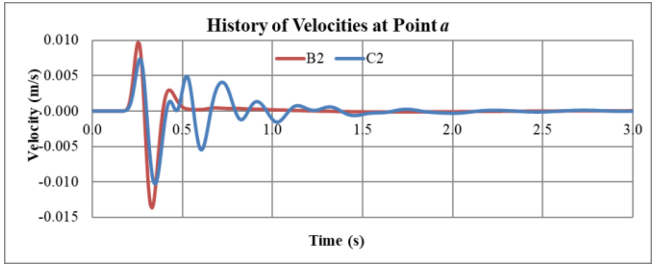
- Velocity amplitude reduced at the dam base
- Dam presence disturbs the uniform wave form
- Foundation block model used in deconvolution vs. foundation-dam model used in the time analysis



High Frequency Pulse	Point	Case B1	Case C1	Case C3
Maximum velocity	*c*	0.0104	0.00903	0.00903
	j	0.0104	0.00903	0.00903
Minimum velocity	*c*	-0.0103	-0.0121	-0.0121
	j	-0.0103	-0.0121	-0.0121



Low Frequency Pulse	Point	Case B2	Case C2	Case C4
Maximum velocity	*c*	0.00623	0.00611	0.00611
	j	0.00623	0.00611	0.00611
Minimum velocity	*c*	-0.00641	-0.00717	-0.00708
	j	-0.00641	-0.00715	-0.00706



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Conclusions

- We showed that significant errors can arise due to the absence of the free-field boundary condition in FE simulations of wave propagation in an elastic media.
- The most efficient solution for end users would be if the commercial code writers implement such boundary conditions in their products.
- Because of the significant error introduced by neglecting this free-field boundary conditions, this should be a high priority investigations for the engineering community .
- Using a foundation block model in a deconvolution process of the earthquake loads and applying the obtained deconvoluted acceleration record to a foundation-dam model may result in significant analysis errors.