Model Validation in Ground Motion Simulations for Southern California

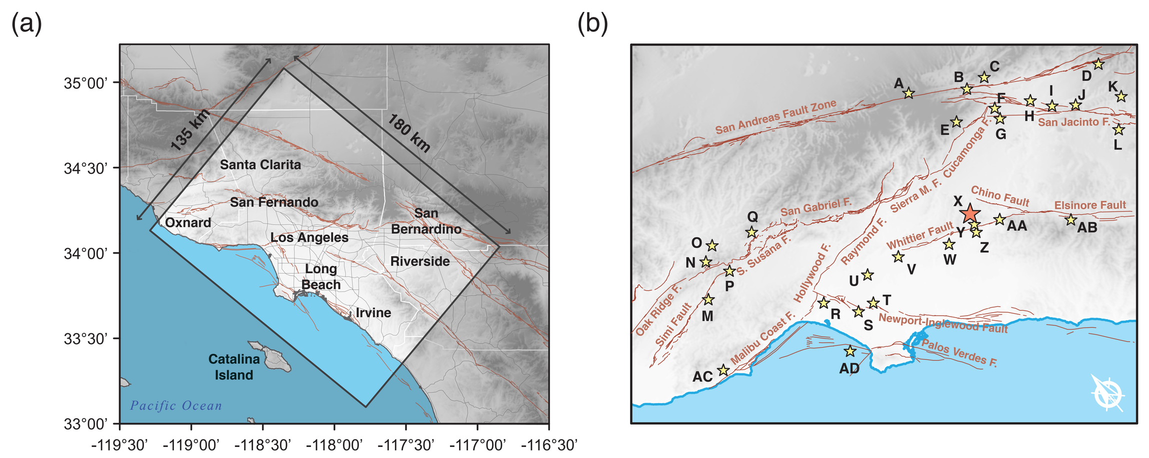
Ricardo Taborda,[1,2] Naeem Khoshnevis[1], Md. Monsurul Huda[1] and Shima Azizzadeh-Roodpish[1,2]

1 Center for Earthquake Research and Information, The University of Memphis
2 Department of Civil Engineering, The University of Memphis

Abstract

We investigate the accuracy of deterministic, regional-scale ground motion simulations of moderate magnitude earthquakes in southern California, and the influence that the models involved have on synthetic results when compared to data. Nowadays, advances in earthquake ground motion simulation algorithms and models, and growth of high performance computing systems and applications facilitate regional-scale simulations of earthquake ground motion using numerical approaches. However, before simulations can be used in engineering practice, much work is needed to confirm the robustness of models and simulation methods. This requires a continuous effort on simulation validation through comparisons with data. We evaluate the accuracy of simulations using quantitative metrics of physical meaning to both seismologists and engineers. We show that validation results are significantly controlled by the choice of the models, including crustal velocity models, attenuation models and parameters, and source models. We focus our attention on the selection of the appropriate velocity model by performing a large set of simulations for multiple past events in southern California, using the different community velocity models available for this region. After identifying the model that consistently yields the best possible approximations, we investigate the influence of different attenuation viscoelastic models, and that of the definition of attenuation parameters and quality factors, as well as the relative influence of point versus extended source models. We concentrate on moderate events in the greater Los Angeles basin area for which there are significant number of high-quality data. We analyze the results through quantitative goodness-of-fit measures and shed light on the relative weight of these factors with respect to each other, and how they influence validation results, and thus simulations as a whole.

Region of Interest and Events



▲ **Figure 1.** Region of interest, events, and simulation domain. (a) Horizontal surface projection of the simulation domain and location of the main cities within it. (b) Events used for evaluation of the velocity models (indicated with star symbols). The Mw 5.4 2008 Chino Hills earthquake, which is used here as a benchmark, is highlighted with a larger, red stat (labeled as event X).

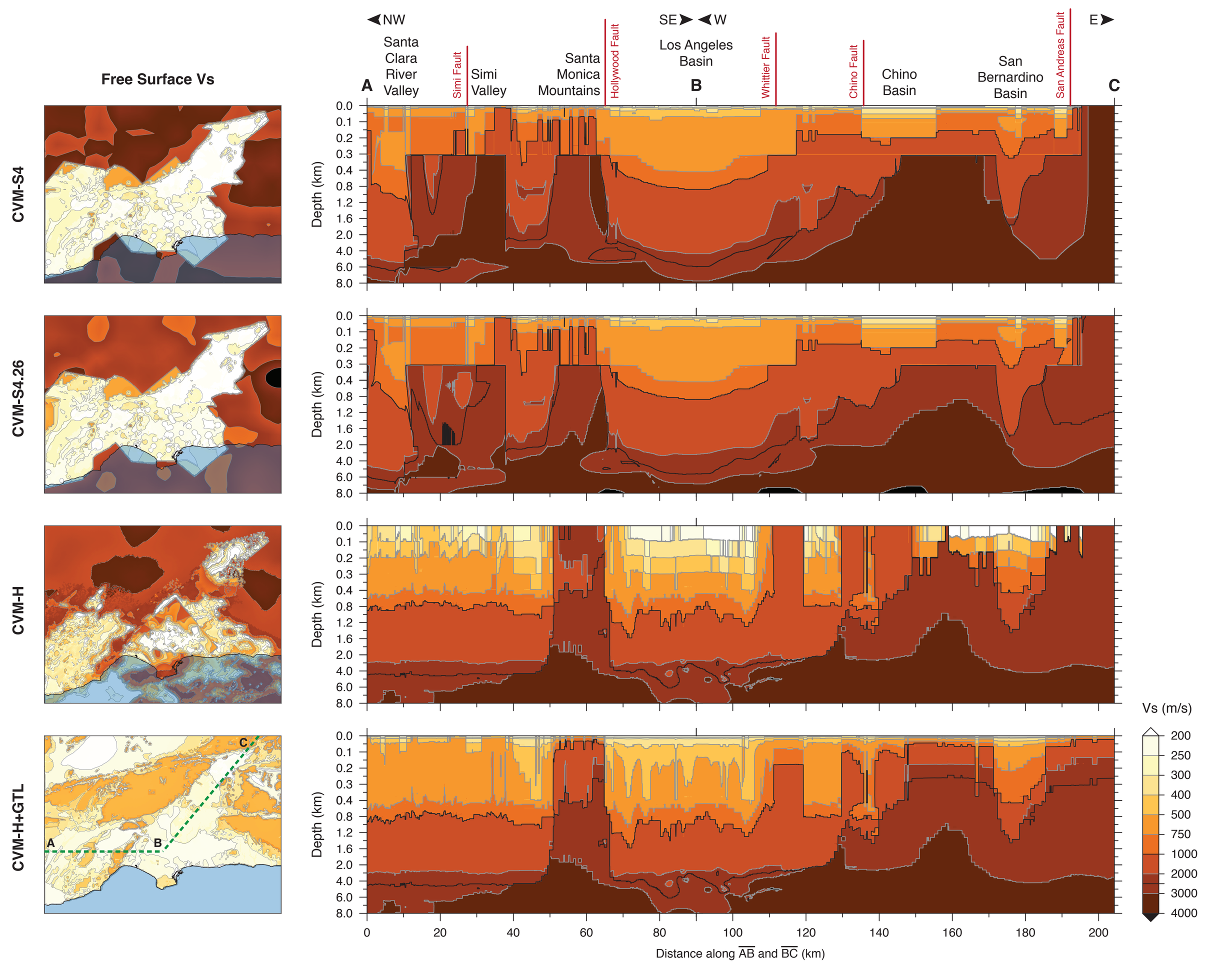
▼ **Table 1.** List of events considered in the evaluation of the velocity models. The location of the events is shown in Figure 1, and the source functions in Figure 3a.

Code	Earthquake name	Event ID	Mw	Coordinates (lon., lat.)	Depth (m)	Strike/Dip/Rake	Date (yyy/mm/dd)	UTC Time (hh:mm:ss)
A	Wrightwood	9064568	4.40	-117.6480, 34.3740	8.99	285/57/86	1998/08/20	23:49:58.198
B	NW of Devore	10972299	3.79	-117.4642, 34.2655	10.91	98/58/68	2001/07/19	20:42:36.470
C	NNE of Devore	14494128	3.72	-117.3838, 34.2587	7.18	344/69/-33	2009/08/01	12:55:55.317
D	Yucaipa	14155260	4.88	-117.0113, 34.0580	11.61	75/59/55	2005/06/16	20:53:26.225
E	N of Rancho Cucamonga	10216101	3.60	-117.5762, 34.2058	4.92	54/69/16	2006/11/04	19:43:44.376
F	2002 Fontana	13692644	3.74	-117.4288, 34.1613	6.54	233/72/-28	2002/07/25	00:43:14.872
G	2005 Fontana	14116972	4.42	-117.4387, 34.1250	4.15	222/88/-25	2005/01/06	14:35:27.593
H	San Bernardino	10370141	4.45	-117.3042, 34.1073	14.22	87/70/28	2009/01/09	03:49:46.051
I	N of Loma Linda	9140050	4.37	-117.2525, 34.0500	15.36	270/90/-6	2000/02/21	13:49:43.017
J	Redlands	10541957	4.10	-117.1797, 34.0045	8.53	33/46/-68	2010/02/13	21:39:06.349
K	2010 Beaumont	10530013	4.28	-117.0232, 33.9322	13.93	234/89/9	2010/01/16	12:03:25.345
L	2006 Beaumont	14239184	3.90	-117.1122, 33.8560	11.53	45/31/-25	2006/07/10	02:54:43.809
M	Simi Valley	14000376	3.59	-118.7530, 34.2722	13.81	234/62/60	2003/10/29	23:44:48.206
N	WSW of Valencia	9753489	3.90	-118.6678, 34.3705	14.21	83/62/57	2002/01/29	06:00:39.140
O	N of Pico Canyon	9096972	3.98	-118.6090, 34.3980	11.53	287/55/54	1999/07/22	09:57:23.502
P	Chatsworth	14312160	4.66	-118.6195, 34.2995	7.58	82/27/51	2007/08/09	07:58:48.888
Q	Newhall	15237281	3.86	-118.4580, 34.3508	3.59	236/58/33	2012/10/28	15:24:23.172
R	Beverly Hills	9703873	4.24	-118.3885, 34.0590	7.90	262/81/4	2001/09/09	23:59:17.695
S	Inglewood Area	10410337	4.70	-118.3357, 33.9377	13.86	243/60/25	2009/05/18	03:39:36.126
T	NW of Compton	9716853	3.98	-118.2702, 33.9290	31.13	116/68/71	2001/10/28	16:27:45.388
U	Downtown Los Angeles	9093975	3.77	-118.2180, 34.0100	9.53	125/49/79	1999/06/29	12:55:00.371
V	Whittier Narrows	14601172	4.44	-118.0817, 33.9923	18.85	282/36/73	2010/03/16	11:04:00.026
W	La Habra	15481673	5.10	-117.9300, 33.9200	5.00	239/70/38	2014/03/29	04:09:42.970
X	Chino Hills	14383980	5.39	-117.7613, 33.9530	14.70	47/51/32	2008/07/29	18:42:15.960
Y	2002 Yorba Linda	9818433	4.75	-117.7758, 33.9173	12.92	34/84/-10	2002/09/03	07:08:51.675
Z	2009 Yorba Linda	10399889	3.98	-117.7892, 33.8940	4.23	208/65/26	2009/04/24	03:27:49.840
AA	ESE of Yorba Linda	9644101	3.64	-117.6882, 33.8777	3.59	56/65/37	2001/04/13	11:50:11.916
AB	Lake Elsinore	10275733	4.73	-117.4770, 33.7322	12.60	65/59/58	2007/09/02	17:26:14.827
AC	Westlake Village	10403777	4.42	-118.8825, 34.0667	14.17	254/73/30	2009/05/02	01:11:13.084
AD	Hermosa Beach	14738436	3.69	-118.4578, 33.8572	11.23	57/41/54	2010/06/07	23:59:27.165

Validation Method

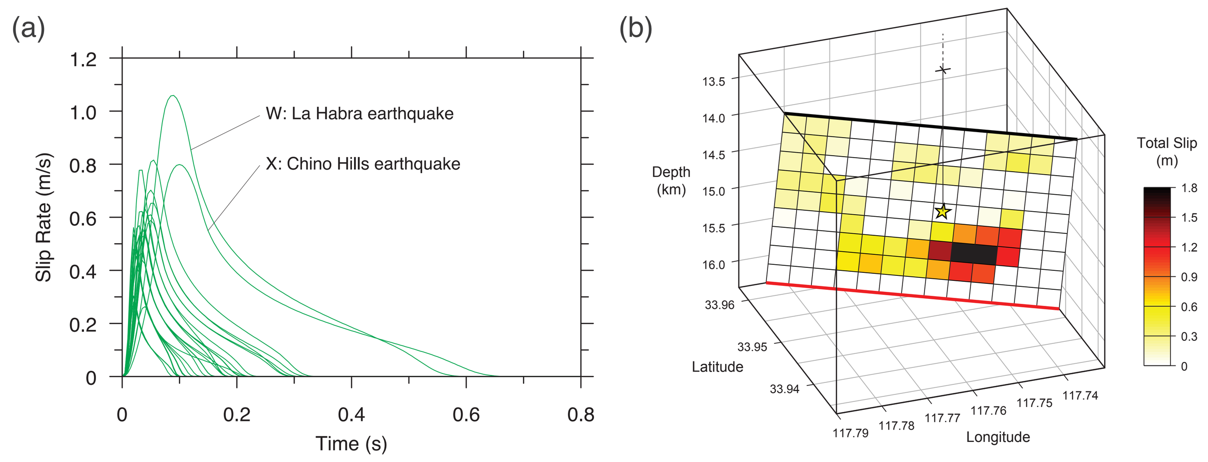
We evaluate the accuracy of simulations based on quantitative validation between synthetics and data at locations where records were available for the simulated events. The validation process is done using the goodness-of-fit (GOF) method proposed by Anderson (2004), with minor modifications by Taborda and Bielak (2013). The method compares synthetics against data using eleven individual parameters: Arias intensity integral (C1), energy integral (C2), Arias intensity value (C3), total energy (C4), peak acceleration (C5), peak velocity (C6), peak displacement (C7), response spectrum (C8), Fourier amplitude spectrum (C9), cross correlation (C10), and strong-phase duration (C11). Each parameter is mapped onto a numerical scale ranging from 0 to 10, where a score of 10 corresponds to a perfect match. The scores are computed for different frequency bands, and ultimately combined into a final score.

Velocity Models



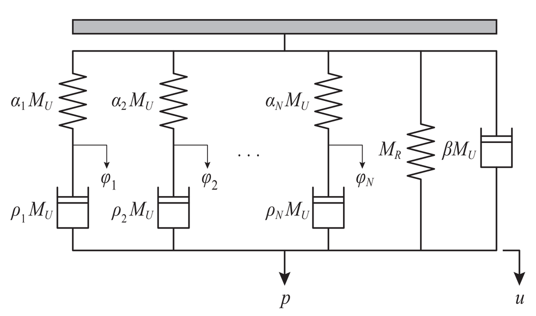
▲ **Figure 2.** Comparison between the southern California community velocity models considered. Left: free-surface shear wave velocity. Right: Vertical profiles of shear wave velocity along the segments AB and BC shown in the bottom left frame. Markers and labels at the top indicate crossings of the profiles through significant geological structures and seismic faults. The vertical scales of the profiles are unevenly exaggerated in three segments from 0 to 0.4 km, 0.4 to 2 km and 2 to 8 km to highlight the differences between the models, especially near the surface.

Source Models



▲ **Figure 3.** (a) Slip rate time functions (slip-rate) used in the point-source models. These source functions were estimated from empirical equations based on magnitude. The source functions of events W and X, corresponding to the 2014 Mw 5.1 La Habra and 2008 Mw 5.4 Chino Hills earthquakes. These two events are the largest of all earthquakes considered. (b) Finite fault model used in additional simulations of the 2008 Mw 5.4 Chino Hills earthquake. The rupture description corresponds to the source inversion done by Shao et al. (2012). The star indicates the location of the hypocenter at 14.6 km in depth.

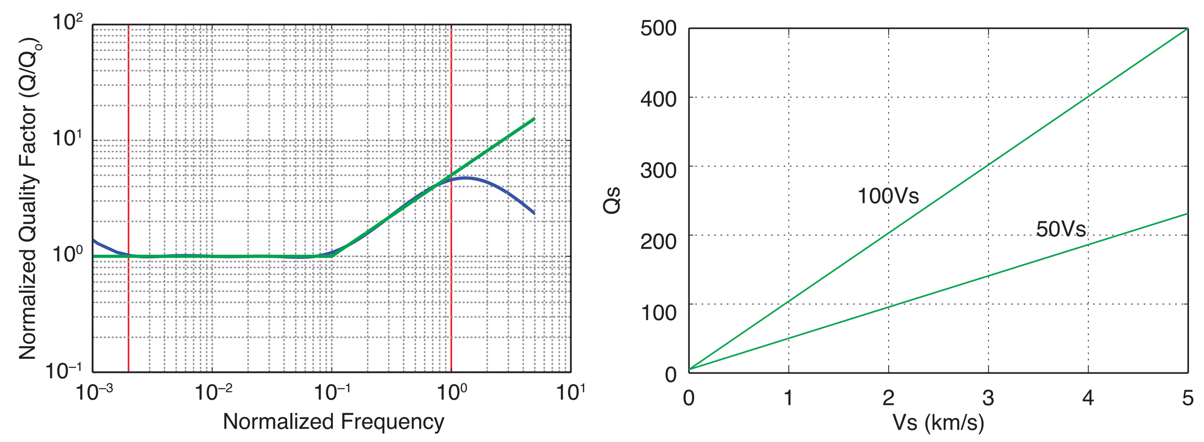
Attenuation Models



◀ **Figure 4.** Intrinsic attenuation is introduced using a viscoelastic model proposed by Bielak, Karaoglu and Taborda (BKT, 2011). The model uses 2 or 3 Maxwell elements and 1 Voigt element to mimic the effect of internal friction in geomaterials. The model can be adjusted to have a frequency dependent or frequency independent attenuation quality factor according to the power law:

$$Q = Q_0(f/f_0)^\lambda.$$

▼ **Figure 5.** (Left) Adjustment of the BKT model to an idealized model with frequency dependent Q attenuation. (Right) Different Qs-Vs relationships used in the simulations in order to set the material properties in the model.



Simulations

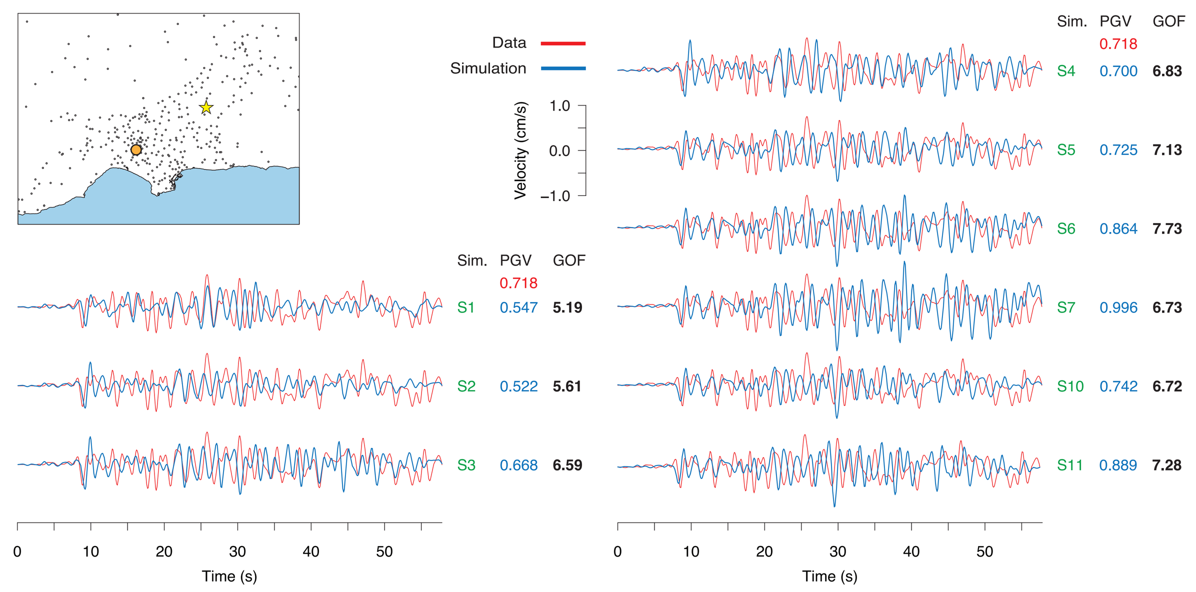
The simulations are done with Hercules, a software for earthquake ground motion simulation, which implements a finite element solution to the 3D anelastic wave equation.

▼ **Table 2.** Different combination of simulations for the particualr case of the 2008 Mw 5.4 Chino Hills, California, earthquake, using variable: velocity models, minimum shear wave velocity, number of points per wavelength, attenuation models, attenuation Qs-Vs relationships, source models, and deffects in the earthquake magnitude.

Sim. ID	CVM-S		$V_{S\min}$		Pts. per wavelength		α in $Q_S = \alpha V_S$		λ in $Q(f) = Q_0 f^\lambda$			Source		Magnitude		
	4	4.26	200	500	10	20	50	100	0 (a)	0 (b)	0.8 (b)	Point	Ext.	5.4	5.45	5.5
S1	•			•	•		•		•			•		•		
S2		•		•	•		•		•			•		•		
S3		•		•	•			•	•			•		•		
S4		•	•		•			•	•			•		•		
S5		•	•		•			•	•				•	•		
S6		•	•		•			•		•			•	•		
S7		•	•		•			•			•		•	•		
S8		•		•		•		•		•			•	•		
S9		•		•		•		•			•		•	•		
S10		•		•	•			•	•				•	•		
S11		•		•	•			•		•			•	•		
S12		•		•	•			•		•			•		•	
S13		•		•	•			•		•			•			•

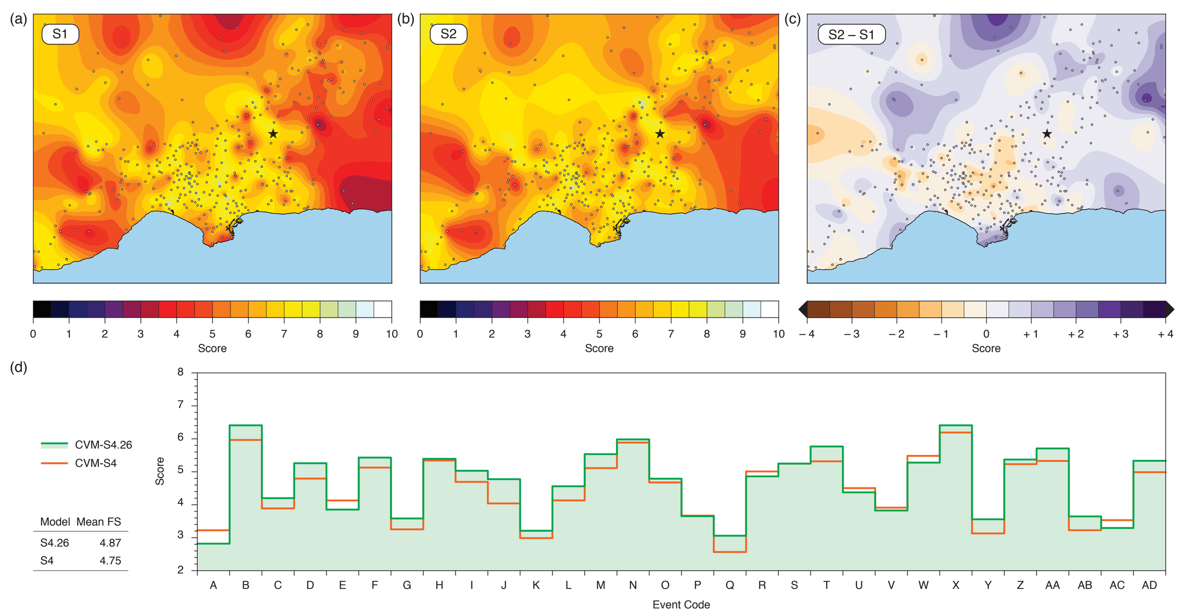
(a) This corresponds to the attenuation model BKT2, which is frequency independent.
(b) This corresponds to the attenuation model BKT3, which can be frequency dependent if λ ≠ 0.

Results



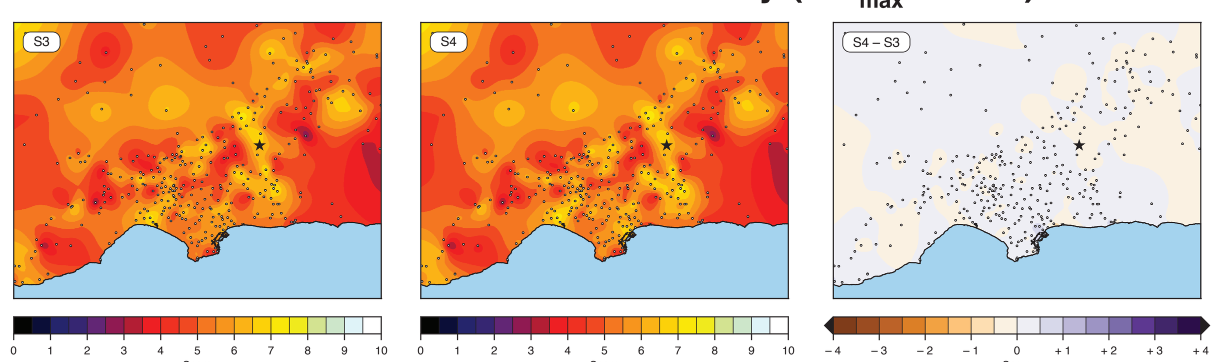
▲ **Figure 6.** Comparison of synthetics for a subset of the simulations described in Table 2, for the east-west component of motion at a sample station near downtown Los Angeles.

Influence of Velocity Models



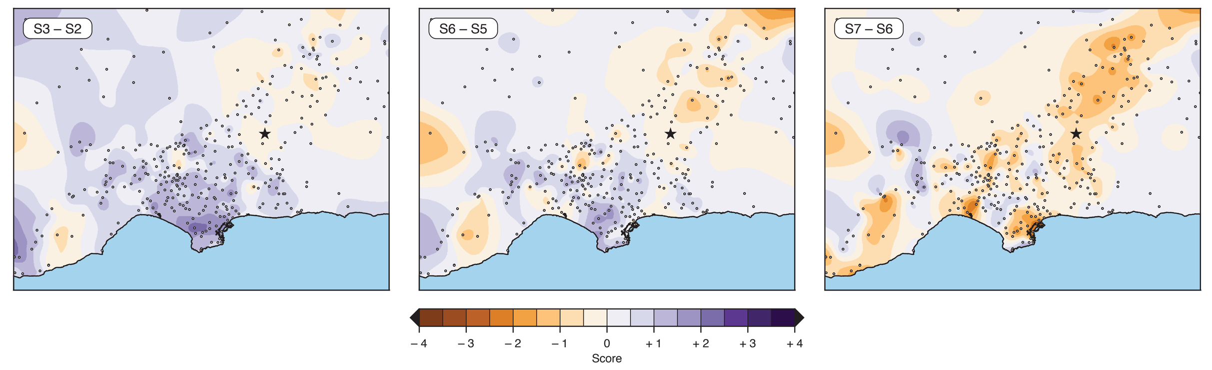
▲ **Figure 7.** (a) Goodness-of-fit scores map obtained for the 2008 Chino Hills earthquake in the frequency range 0–1 Hz using the velocity model CVM-S4, i.e. simulation S1. (b) Same as before, but corresponding to results obtained using the model CVM-S4.26.M01, i.e. simulation S2. (c) Difference between the previous two maps (or GOF residual map), where positive values indicate improvement in S2 with respect to S1. (d) Summary chart of the final average GOF scores obtained for all events in Figure 1b.

Influence of Minimum Shear Wave Velocity (at f_{max} = 1 Hz)



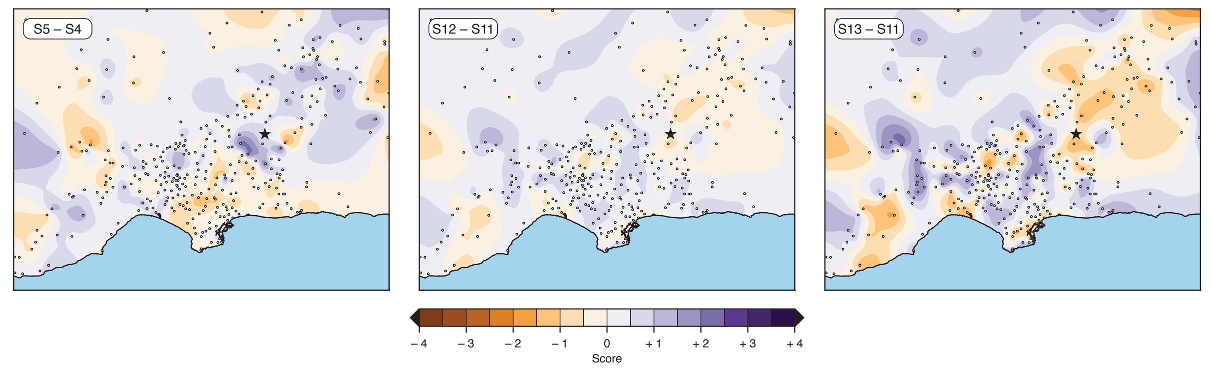
▲ **Figure 8.** Left and center: GOF maps for simulations S3 and S4, respectively, for different minimum Vs (see Table 2). Right: GOF residual map obtained between simulations S3 and S4. Positive values indicate improvement in the validation results.

Influence of Attenuation Q Models and Parameters



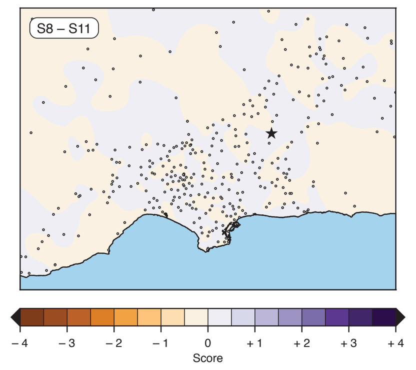
▲ **Figure 9.** GOF residual maps obtained between simulations S2 and S3, and S5, S6 and S7. Left: effect of using Qs = 50Vs versus 100Vs (S3 – S2). Center: effect of using the models BKT2 versus BKT3 under frequency independent attenuation (S6 – S5). Right: effect of using frequency dependent attenuation with an exponential slope of λ = 0.8 with respect to the case of frequency independent Q (S7 – S6).

Influence of Source Models and Magnitude Uncertainty



▲ **Figure 10.** Similar to Figure 9 but now showing GOF residual maps obtained between simulations S4 and S5, and S11, S12 and S13. Left: effect of using an extended source model instead of a point source (S5 – S4). Center: effect of scaling the magnitude of the earthquake to Mw 5.45 instead of 5.4 (S12 – S11). Right: effect of scaling the source to magnitude Mw 5.5 instead of 5.4 (S13 – S11).

Influence of Numerical Model Resolution



◀ **Figure 11.** Similar to Figurs 9 and 10 but now showing the GOF residual map obtained for simulations S8 – S11. These residuals show the effect of using double the number of points per wavelength in the generation of the finite element mesh.

Conclusions

Upon performing a collection of simulations with varying velocity models for a large collection of events, and with varying attenuation and source models for the case of the 2008 Mw 5.4 Chino Hills, California, earthquake, we find that the results obtained from quantitative validation analysis using goodness-of-fit metrics are significantly sensitive to the modeling and simulation parameters. Initial statistical analysis ran on these results not included here for brevity indicate that the GOF scores within any given simulation tend to exhibit standard deviations of about ±1 GOF points. This means that under any given conditions, the GOF scores may oscillate within a range of about 2-points. Considering the GOF scale used here categorizes the quality of the fit from poor to excellent in 2-point bins, this variability helps to constrain the level of uncertainty on the parameters used for (physics-based) ground simulation.

Acknowledgements

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