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STRANGER THINGS IN SEISMIC RESPONSE AND STATISTICAL TOOLS TO RESOLVE THEM

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Abstract: *Demogorgons, monsters, and mythical creatures do not appear only in Soviet research labs, secretive government facilities or just plain Hawkins, Indiana. They frequently cross-over to earthquake engineering in the form of questions that conform to the paradigm of "Does X matter in seismic response?". X can be a seismological characteristic, such as duration, vertical component, incident angle, or near-field directivity; it can also be a structural property, such as building period, rocking block size, or plan asymmetry. We, as investigative structural engineers, are vastly more familiar with the latter set of queries and we are clearly better equipped to handle them. We can sometimes even provide definitive answers that most, if not all of us, would agree upon. Instead, questions involving seismological characteristics seem to leave us baffled and stuck in an Upside Down world that resembles structural engineering but is not exactly the same. Wading through its murk, it is good to have some investigative tools and processes that will help us find our way home. In the end, though, we may end up equal parts enlightened and confused, as most questions of whether something of the seismologist world matters for the structural one are nearly-universally answered by uttering "It depends".*

The vanishing of simple answers

Analytical methods have had their heyday. Most of the things that could be proven unambiguously were done so several decades ago. Even then, this was hard to do when your driving factor (or load) is a non-analytical waveform, as indecipherable as an earthquake ground motion. The days of using idealized pulses or sinusoidal waves have more-or-less passed. Now it is empirical data processing and statistics that can push the way forward, testing hypothesis and accepting or rejecting them before moving on to the next one. Artificial Intelligence may be able to help at some point, but as we are seeking insights, its fundamental unexplainability (despite efforts to the contrary) may impede our goal of finding answers that are general enough to deserve recognition or publication.

Front and foremost are questions about the influence of different ground motion characteristics on structural and non-structural responses. This includes soil site characteristics, the magnitude and distance of the rupture, the duration, spectral shape, pulsiveness, or incident angle of the ground motion etc. In each case, the goal is simple: The abundance of metrics that characterize each ground motion recording can make any analysis biased if the influence of an important metric is disregarded. Correcting for this would at least mean that, in the concept of running nonlinear response history analysis in one or more of its various forms (cloud, multi-stripe, or incremental dynamic analysis, Jalayer and Cornell 2009), the record suite employed to represent one or more intensity levels should be consistent with the distribution of said metrics that characterizes the site. Add enough metrics and the situation becomes untenable. If you do not believe this, try selecting ground motion records for a site influenced by different tectonic regimes, e.g., subduction, interface, or crustal motions (Tremblay and Atkinson 2001, Chandramohan et al. 2016), where some seismic sources can be near enough to potentially introduce directivity effects. Feel free to double the trouble by attempting this at a regional scale and realizing that the different suits of ground motions needed to characterize the fragility of any single building at any single site will mean that you will end up with site-dependent fragilities that may or may not match depending on the intensity measure employed (Kohrangi et al. 2017). Your only salvation is to reduce the parameters of the problem down to a manageable set that you can tackle within your budgetary, time, and workforce constraints. In this, you have two options: Either blindly pick a direction (i.e., ground motion set) and try to wade through the murk and may Goddess Luck help the bold, or you can look for a flashlight bright enough to help you find your way.

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In many ways, what we are saying here is not exactly alien to the world of earthquake engineering. Structural engineers have a long tradition of working with different structural characteristics and deducing whether they matter or not. Stiffness, strength, and period characteristics were among the first to be deciphered, and the conclusions largely form the basis of our design and rehabilitation practices. Plan asymmetry (Marusic and Fajfar 2005, Aziminejad and Moghadam 2010), mass/stiffness/strength irregularities along the height (Fragiadakis et al. 2006, De Stefano and Pintucchi 2008), soil site characteristics (Mylonakis and Gazetas 2000, Miranda 1993), backbone characteristics (Vamvatsikos and Cornell 2006) are examples that come to mind. Still, this does not mean there have not been any hiccups, such as whenever one approaches earthquakes as quasi-static deterministic problems rather than probabilistic dynamic ones, where the real nature of issues such as hysteretic energy dissipation (Kazantzi and Vamvatsikos 2018) or incident angle (Giannopoulos and Vamvatsikos 2018, Skoulidou et al. 2019) may be misinterpreted and their real influence misjudged by disregarding the true nature of seismic loading.

In other words, every time an engineer tries to peek through the Upside Down world of seismology, she/he is prone to mistakes and bias without the proper tools. Probably the same goes for our seismologists when trying to peer into our tidy little world of structural engineering, as things that matter to us (think absolute acceleration spectrum) are fundamentally different to things that matter to them (picture Fourier amplitude spectrum). What characteristics one should carry with her/him when crossing the border of the two worlds is of utmost importance in ensuring that our engineering conclusions bear witness to the miracles of seismology and represent the true unbiased facts rather than a biased mythology with little basis in reality.

Staying true to our probabilistic and empirical data basis, we are going to discuss exactly these tools that will make us see through the haze and find answers that hold to scrutiny.

Statistics, do you copy?

When things get hairy, sometimes you just need to reach for that radio set and call for help into the unknown. Statistics should be your first responder and best friend whenever in need of sifting through hazy data and deciphering hidden nuances of influence. Remember that in all cases there are two important questions that you need to answer when asked “Does X matter?”. The first is whether there is any statistical significance, in other words, whether we can find any effect of X when looking with the best magnifying glass that our data allows. This is the scary realm of hypothesis testing and p-values that has frustrated generations of university students in their early academic years. Actually, it has caused no less frustration for full grown veteran researchers (Salsburg 1985, Ioannidis 2005, Nuzzo 2014). In properly understanding such tools we find that it is often useful to look to other scientific fields where digging through abysmal amounts of data in search of statistical significance is everyday practice. Prime among them is medicine.

As it turns out, looking for significance in a large data set can often produce some surprising results. One famous example by Schoenfeld and Ioannidis (2013) concerns the use of everyday cooking materials and their association with cancer. If you look hard enough, you can find some benefits or detriments to every ingredient in our everyday cooking. The real question, though, is not just statistical significance, but whether said effects are of any practical importance. In other words, once you are done looking through the magnifying glass to recognize the existence of an influential parameter, you need to step back and ask yourself whether said influence can be safely discarded in view of other uncertainties that may overwhelm it. Thus, while it may be scientifically argued that having a mosquito sit on your head during weighing will certainly increase your estimated weight, it would be a far stretch to claim that you need to watch for mosquitos when weighing yourself, lest they bias your results. Thus, looking for statistical as well as practical significance should be practiced together as both are indispensable concepts in properly answering causality questions.

Going back to our medicinal association, one needs to borrow two important concepts: Comparing effects with paired versus unpaired (or independent) samples. Paired sample testing is quite familiar in medical contexts where monozygotic twins have been studied extensively to understand the effect of different environmental traits once genetics are taken out (Nilsen et al. 2013, Sahu and Prasuna 2016). The high power of such tests allows a quick discerning of the effect differences in the treatment of the two twins (or sampled pairs in general). On the other hand, independent sample testing requires much larger sample bases, as the two samples being compared now contain a lot more noise that needs to be quenched.

In the same manner, seeking paired samples is by far the optimal way to discern the effect of different characteristics in earthquake engineering. This has been naturally exploited by researchers for a long time when seeking to understand the effect of structural characteristics on the response. It is only logical to employ the same set of ground motions and vary the characteristic of interest in a controlled manner (avoiding unnecessary changes to other aspects of each structure) to ensure a very close comparison of response under one record against another. This is a natural way to pair things and it has been exploited in numerous studies (e.g., Fragiadakis et al. 2006). What is far more difficult, is achieving paired samples when trying to vary the ground motion characteristics. Then, assuming you want to work with natural recorded ground motions, you are by definition out of the realm of twinning. Ground motions are sui generis, and changing any characteristic means going to a different recording, thus fundamentally changing the entire waveform.

In the authors' opinion, this was the rather bleak outlook in the field until the groundbreaking work of Chandramohan et al. (2016), and their idea of spectral equivalence. The premise is fairly simple: (a) Engineers all seem to care about the absolute acceleration spectrum; (b) the Conditional Spectrum (Lin et al. 2013) approach offers a good way to select ground motions that match the expected spectral shape (and its distribution) at a given site; (c) if we select pairs of motions that when scaled have a closely matching spectrum, then we can use them to test for the influence of all other remaining non-spectral characteristics. In other words, if we substitute spectral shape for DNA, we now have a way to find twins in naturally recorded ground motions.

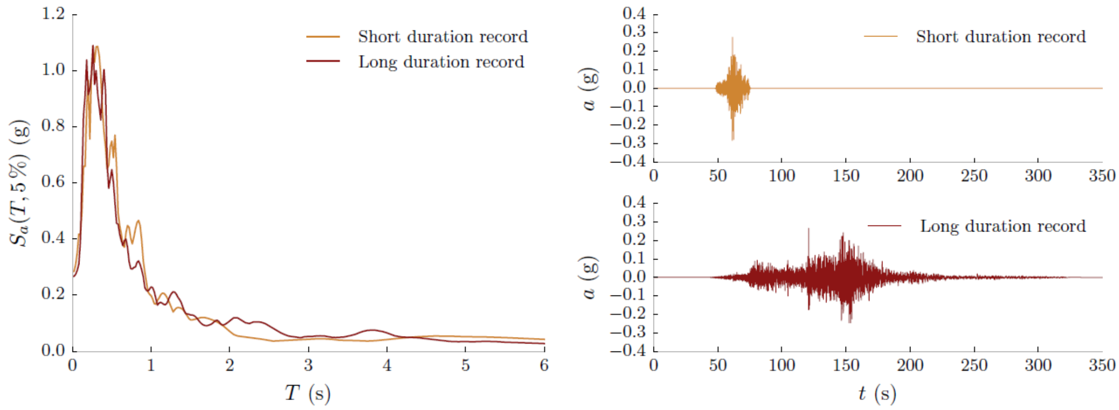


Figure 1. An example of spectrally-matched short and long duration motions (from Chandramohan et al. 2020)

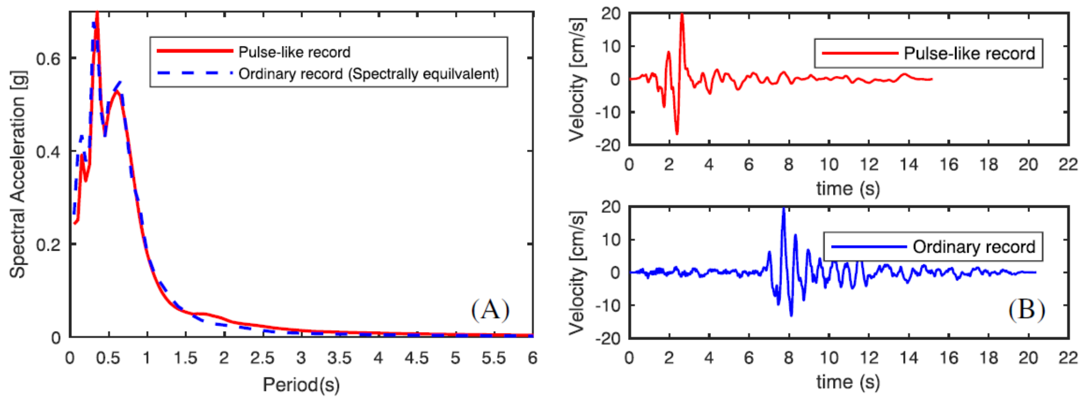


Figure 2. An example of spectrally-matched pulse-like and ordinary motions (from Kohrangi et al. 2019)

The battle of the rocking block

To better frame this discussion, let us move away from our familiar landscapes of multi-story structures, steel, reinforced concrete, and ductile response. Let's check out a deceptively simple system that is straight out of the Upside Down world: The rigid rocking block. In its simplest form (Housner 1963), it is a rectangular 2D block of uniform density, height 2*h*, and width 2*b*, which can only rotate around its edges, rocking about them as shaken by the ground motion without sliding or bouncing (Figure 3). Impact is handled by the restitution coefficient η that relays the ratio of the amplitude of vertical velocities before and after impact. Such blocks are characterized by a size parameter

$$p = \sqrt{\frac{3g}{4\sqrt{b^2 + h^2}}} \quad (1)$$

and a shape parameter, α, termed slenderness or stability angle:

$$\alpha = tan^{-1}(b/h) \quad (2)$$

It is well known that the response heavily depends on *p*, as this is akin to a frequency parameter of the block. Things are not so clear regarding α. Its value clearly influences the response of the system (Makris and Kampas 2016). Still, a long-standing question concerns the parameterization of its response. Specifically, is the seismic response of a rigid rocking block normalizable by the slenderness ratio? In other words, if you were to build a predictive relationship for the rotation (or overturning) of a rocking block, can you remove the slenderness ratio from the parameters to consider? The answer is a yes when slender blocks and simple analytical pulses are involved (Dimitrakopoulos and DeJong 2012). This is a classic case where seismology has been effectively cut-out from the problem, and our structural engineering world stays contained in its own bubble. Things make sense and our analytical tools do not fail us. However, when the Upside Down world of seismology bleeds in and *actual* ground motions are involved, the uncertainty brought in by record-to-record variability makes our path murkier and statistical investigative tools need to be brought in.

First of all, we need to search for pairs, and if there are none to discover, we need to invent them. Herein, as we are investigating the effect of a fundamentally structural parameter with ground motion input only being the noise in the background, each ground motion under two different "structural treatments" can effectively yield a pair. We will employ two distinct record sets of differing nature: one of 86 ordinary (no pulse, no long duration) ground motions and another of 44 pulse-type ones (Shahi and Baker, 2014).

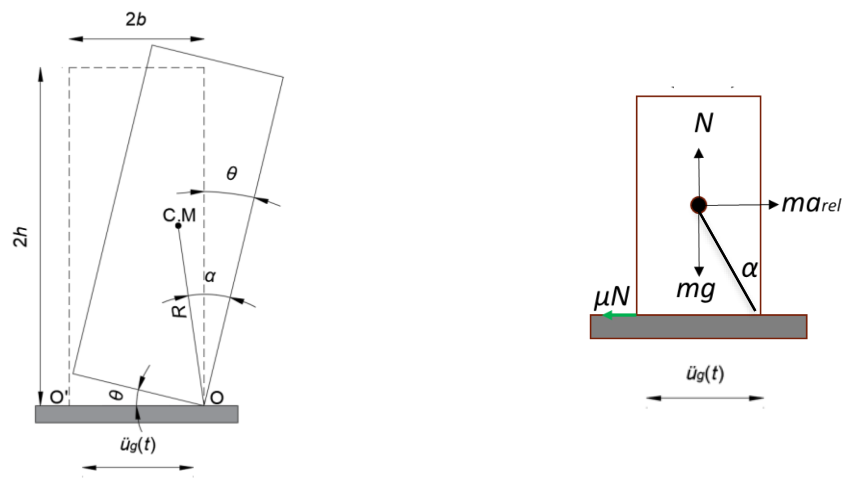


Figure 3. Simple rocking block (left) versus sliding block (right)

If you are already feeling lost in translation, just think of the above approach as follows: You can apply the same ground motion on two (otherwise identical) rigid blocks of different slenderness ratio and compare their normalized responses. Then the only parameter that differs among the two paired cases (i.e., the differing treatment in statistical parlance) is the use of two different α values. In essence, having the same ground motion as input creates the pairing/tying/twinning of the samples. If their normalized responses are the same, or at least no *significant* difference can be discerned, then α should not matter within the limits of what we call *significant*. If not, unfortunately you cannot discount α when trying to predict the (normalized) block response.

Obviously, there are multiple levels of comparison that one can attempt; each comes with its own advantages and can lead to different conclusions regarding the significance of the comparison outcome. Rather than try to explain theoretically all the possibilities out there, let us take a deep breath and dive right in, following in the footsteps of Lachanas et al. (2023) and using as our testbed ten blocks of two different frequency values (p = 1s^{-1} and 3s^{-1}) times five slenderness angles (α = 0.05, 0.10, 0.15, 0.20, 0.25).

Level 1: Individual response histories

The most detailed comparison can be done on the individual ground motion and response history level. Essentially, one can compare the paired samples pitting the response histories of one value of α against the others. As an example, Figure 4 shows the results for three ordinary ground motions, while Figure 5 compares them for three pulse-like ones. In each panel of these figures the ground motions have been scaled to the same value of normalized peak ground acceleration (PGA). Simply by inspection, we can tell that our hypothesis may hold perfectly for some ordinary records (e.g., Figure 4c,d,f) and all pulse-like ones, with the exception of Tabas 1978: the response histories are actually coincident. The same holds when viewing the two record sets in their entirety. Most pulse-like records show coincident responses regardless of α, while ordinary ones are plagued by numerous mismatches where things do not seem to work out as well.

Had we been able to establish such a strong statement of one-by-one, time-instant by time-instant response history correspondence, we would have achieved the highest level of confirmation. This is not the case, nor would we expect it to be the case for most engineering questions that have been already heavily analysed. Yet, we should not despair. For all practical purposes we do not need to have such detailed matching of results. Matching of the peaks should still be good enough, as it is the maximum absolute response that one is typically interested in; this leads us right to our next comparison level.

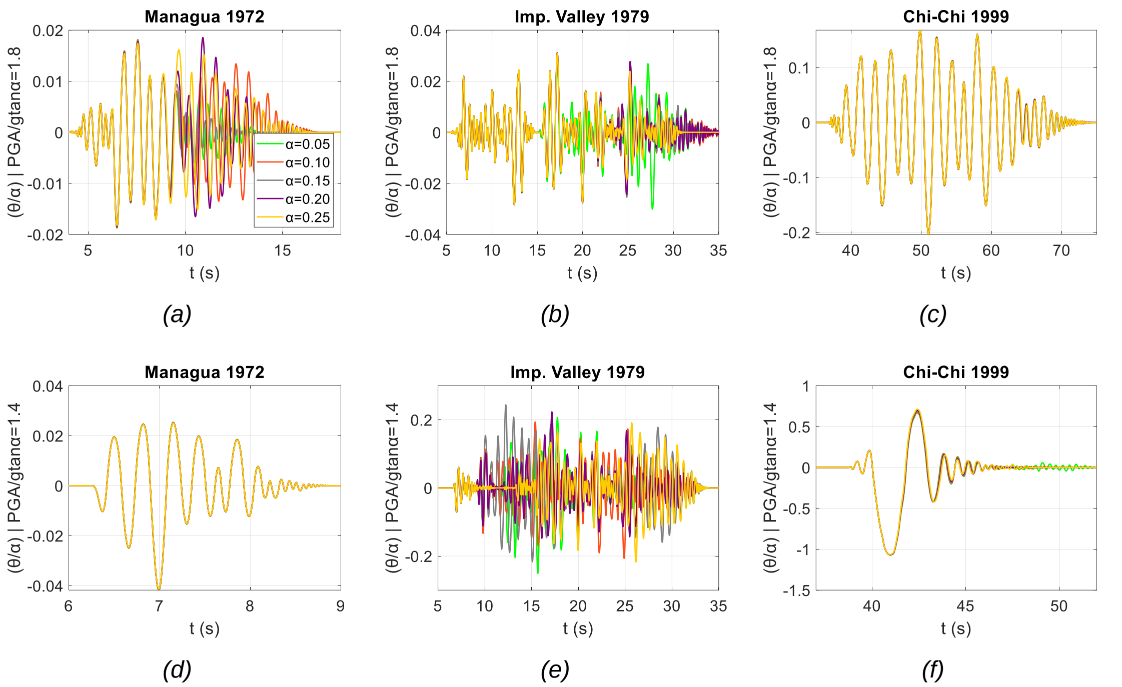


Figure 4. Comparison of individual ground motion response histories for ordinary records scaled at the same normalized intensity level: (a)-(c) blocks with p = 1 s^{-1}, (d)-(f) blocks with p = 3 s^{-1} (adapted from Lachanas et al. 2023).

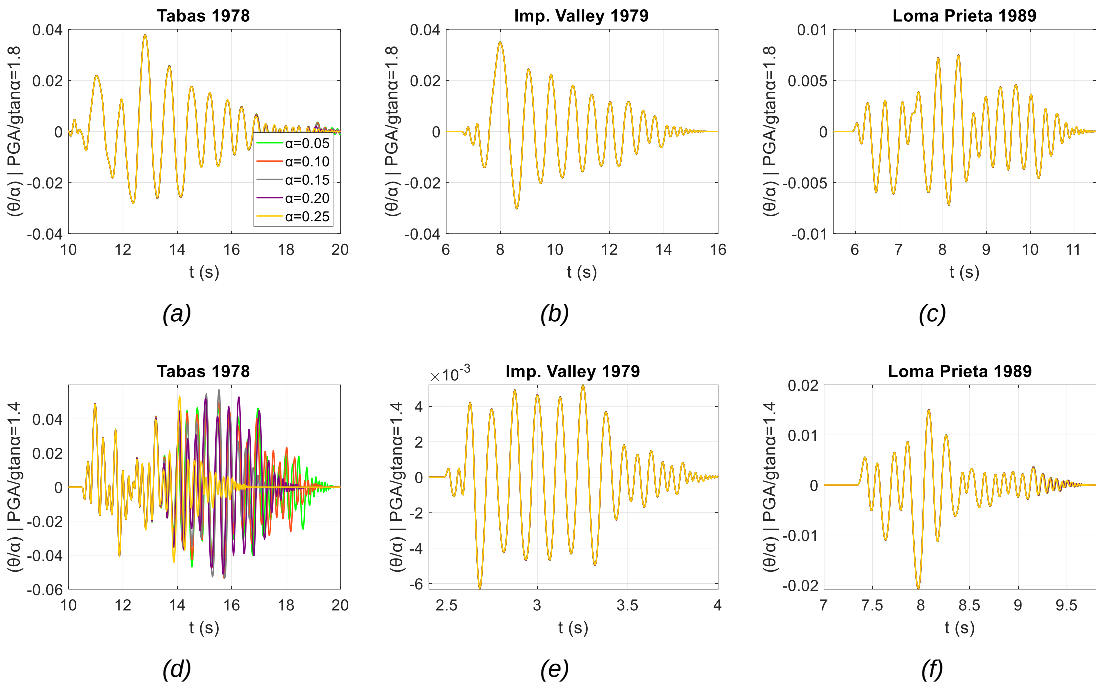


Figure 5. Comparison of individual ground motion response histories for pulse-like records scaled at the same normalized intensity level: (a)-(c) blocks with p = 1 s^{-1}*, (d)-(f) blocks with p = 3 s*$^{-1}$ *(adapted from Lachanas et al. 2023).*

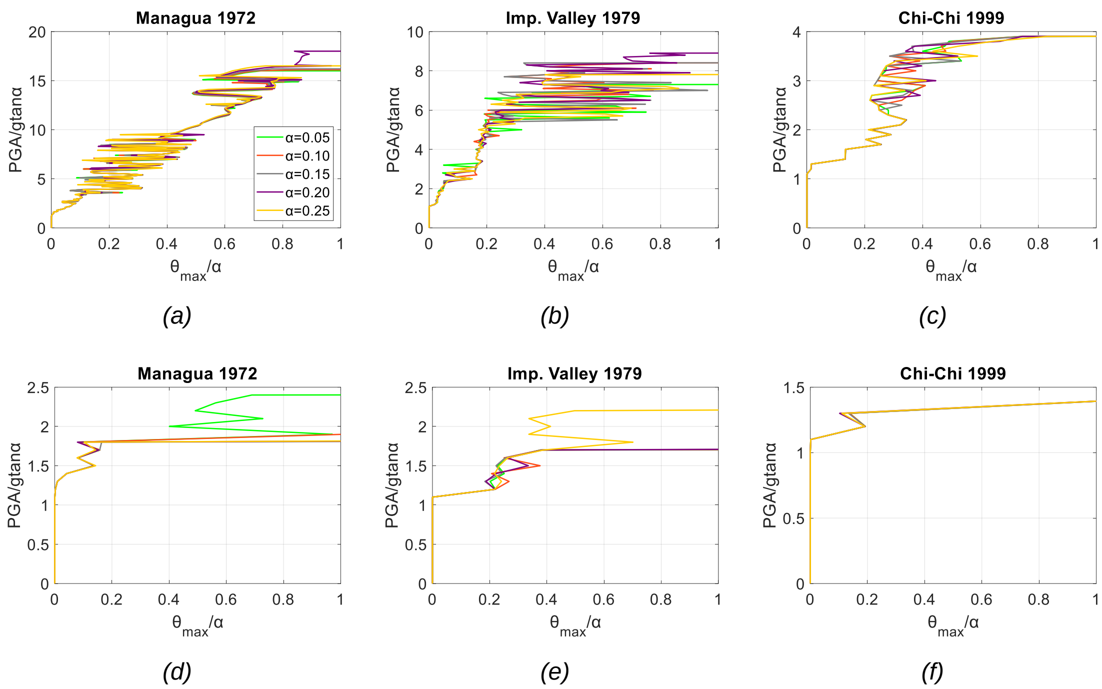


Figure 6. Comparison of individual IDAs for ordinary records: (a)-(c) blocks with p = 1 s^{-1}*, (d)-(f) blocks with p = 3 s*$^{-1}$ *(adapted from Lachanas et al. 2023)*

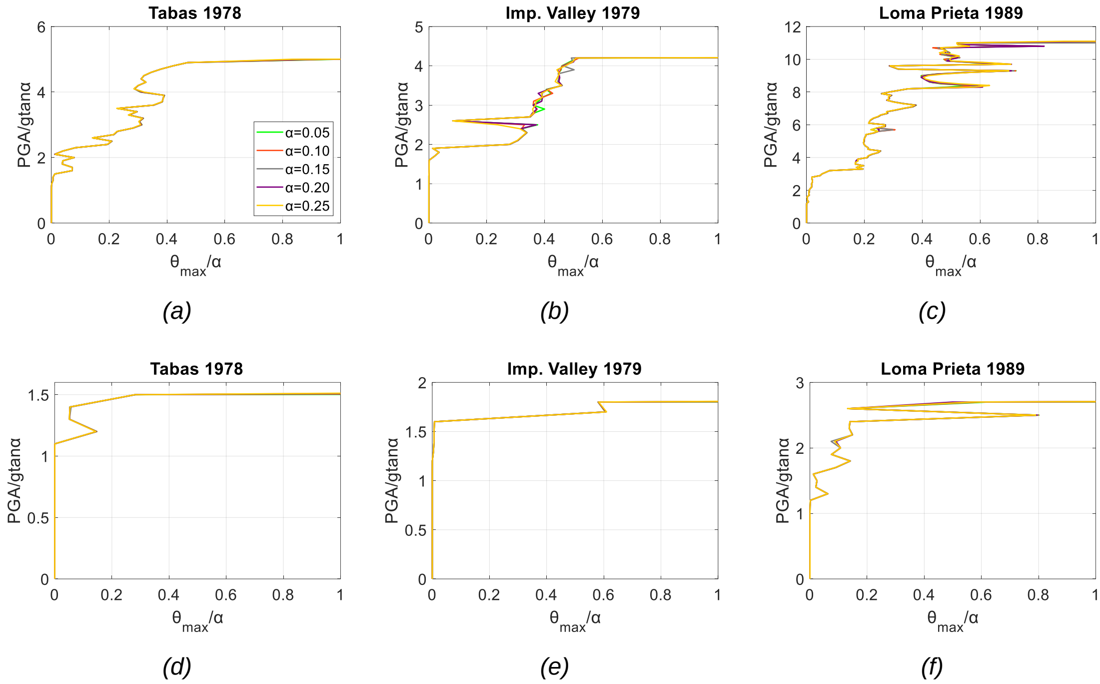


Figure 7. Comparison of individual IDAs for pulse-like records: (a)-(c) blocks with p = 1 s^{-1}, (d)-(f) blocks with p = 3 s^{-1} (adapted from Lachanas et al. 2023)

Level 2: Individual response history maxima

Staying on the earlier track of focusing on individual response histories, let us know turn to their peaks, or maximum absolute values of response to seek a weaker yet highly practical test of our hypothesis. Within the framework of incremental dynamic analysis (IDA, Vamvatsikos and Cornell, 2002), this is akin to comparing individual IDA curves, allowing us a full coverage across the intensity measure range, until block overturning is observed. Figures 6 and 7 show a sample of such results for 3 ordinary and 3 pulse-like motions, respectively. The results show an imperfect, but still fair matching for the ordinary records, while near-perfectly coincident IDAs appear for the pulse-like ones. Actually, the latter result holds across the entire sample of pulsive motions, offering excellent confirmation of intuition gained from research on simple pulses (Dimitrakopoulos and DeJong 2012). On the other hand, some murkiness still persists for ordinary non-pulse-like motions. Nevertheless, Figure 6 does seem to say that the individual results per ground motion record do not seem to change that much from one value of α to another. So, we may be justified to say that while the individual response peaks may not be perfectly matched, perhaps when viewed as an ensemble of records, they will not be too far off. It would be best if we could check that as well.

Level 3: Ensemble paired statistics

Further weakening our premise and focusing on the troublesome case of ordinary records, we are going to look for matching of paired observation *statistics* between samples subjected to the different treatments. In simpler words, we shall set a single block, say with α = 0.10, as the basis and seek the ratio, r_α, of maximum absolute (normalized) response of all other blocks of the same p and different α over the response of the basis block under the same ground motion and same normalized intensity. Again, we seek to control all other variables in our pairing of samples and only leave free the one to test.

The results for different levels of normalized intensity appear in the form of box-and-whisker plots (also known as boxplots) in Figure 8. First, let us focus on the lower range of intensities, noting that rocking occurs at a normalized intensity of PGA/(g tanα)=1. Simply put, one deals with ultra-low levels of response for normalized intensities of up to 1.5, where the block barely uplifts and then sits back down. It should not come as a surprise that the r_α ratios end up having some wide dispersion for such low intensities, simply by virtue of being the ratio of responses that are very close to zero. This response range is of little engineering significance; therefore, it should not feature in our comparison. Interestingly, in practically all cases the boxplots are well centered around a ratio of 1.0, with diminishing dispersion for “rocking-level” intensities above 1.5. Some outliers, i.e., extremely low or high ratios (indicated by crosses in Figure 8), do appear, but they are just the exception to the rule. Put together, to a very high degree of confidence, we can claim that for all practical purposes the value of *α* can be normalized out of rocking response under ordinary motions if we are looking at a large ensemble, rather than a single ground motion. Some exceptions for specific ground motions do exist, but they are a low minority of no statistical significance.

Level 4: Ensemble unpaired statistics

Although the matter is more-or-less already settled, it pays off to consider our last stand in this gradual weakening of our statements on treatment equivalence. This is the comparison of ensemble statistics where direct pairing of the samples is ignored. Herein, we are not seeking to conclude that a given ground motion will produce the same response. Instead, we are relaxing our stance to seek whether the same ensemble of motions will produce the same statistics of response under the two treatments. This can be shown in the form of fractile IDA curves (or in general stripe-by-stripe statistics within a multi-stripe analysis context), as shown in Figure 9 for our 2×5 blocks under the set of ordinary ground motions. Quite clearly, the 16/50/84% fractiles of response given the normalized intensity are a near-perfect match to a high degree of significance (easily testable to satisfaction if needed). Thus, the central value (mean or median) and the dispersion of the response given the intensity can be claimed to be unaffected by *α* given a proper normalization. This offers further evidence and ultimate confirmation that if all we are interested in is the response statistics, then we can safely remove *α* from our concerns.

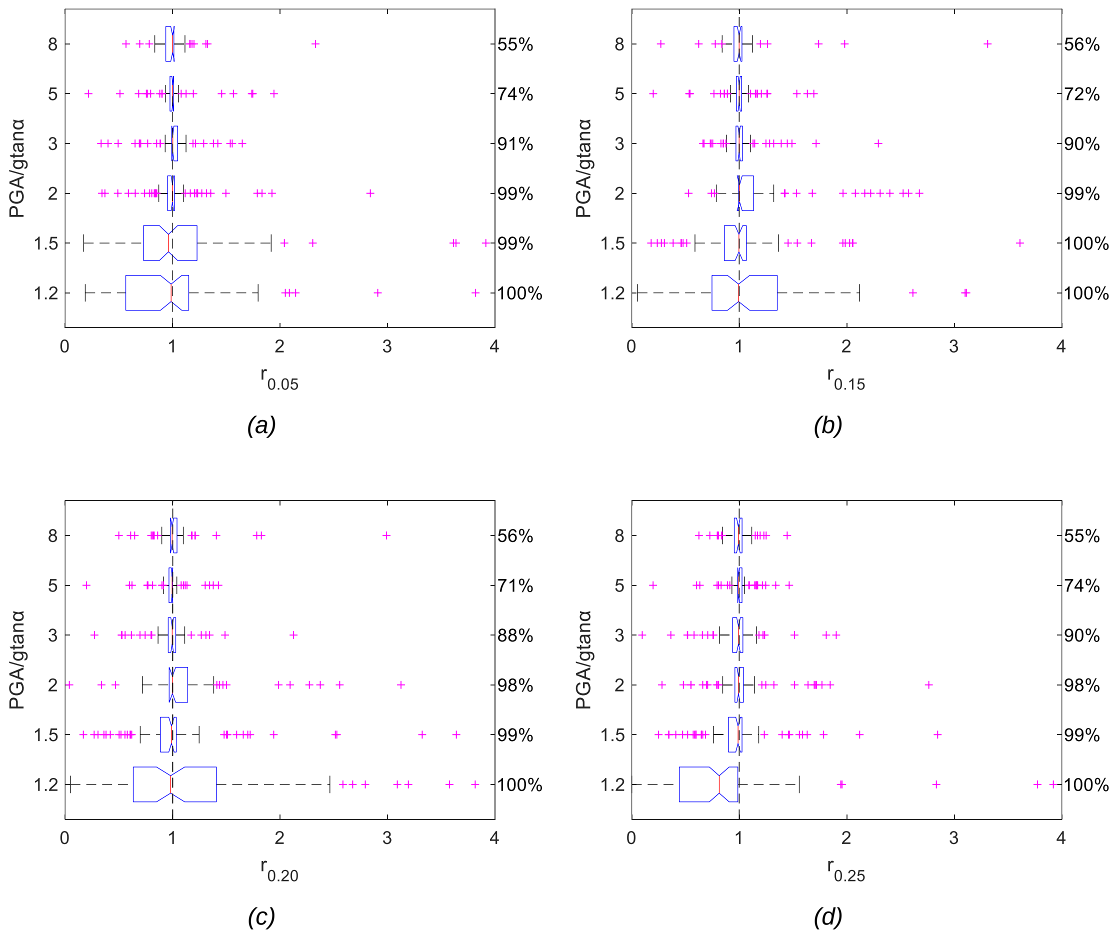
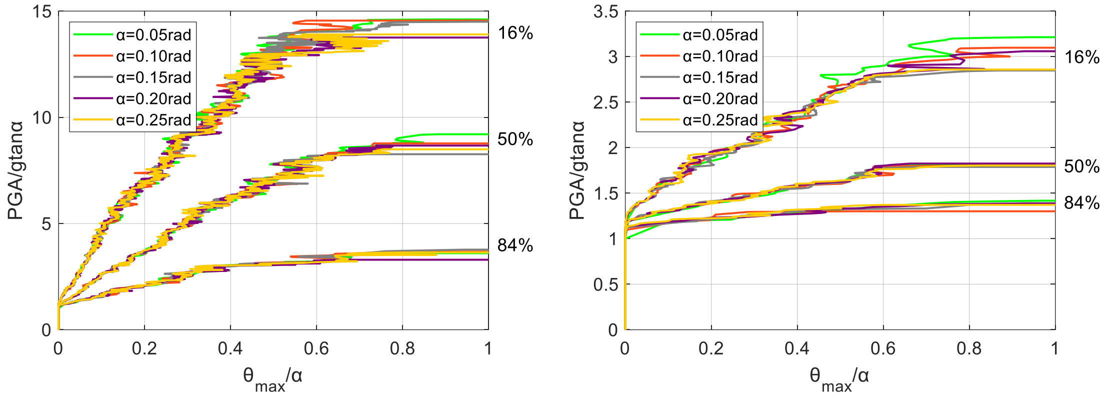
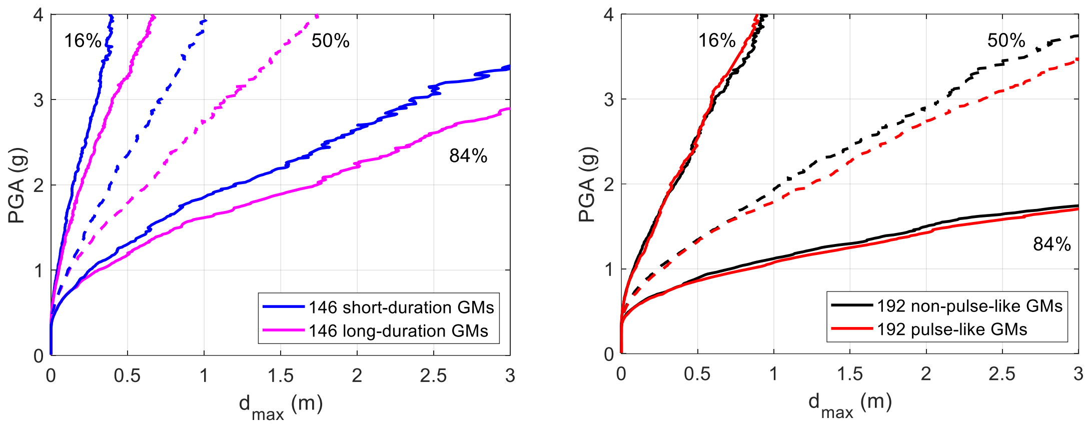


Figure 8. Comparison of pairwise response ratios for ordinary records for blocks with p = 1 s^{-1}. The percentage of noninfinite ratios from 86 total appears on the right vertical edge for each intensity level (from Lachanas et al. 2023)



(a) p = 1 s-1 (b) p = 3 s-1

Figure 9. Comparison of quantile IDAs for ordinary records (from Lachanas et al. 2023)



(a) short versus long duration motions *(b) pulse-like versus ordinary motions*

Figure 10. Comparison of quantile IDAs for rigid block sliding response under two different types of spectrally matched pairs of ground motions

The pairing of the sliding block

Let us now turn to a different problem, involving a purely sliding rigid block on a flat surface that obeys the Coulomb friction model (Figure 3). The sliding response of the system is solely described by the friction coefficient of the interface and the ground motion applied. Our question now is simpler, but no less sinister: Does the duration of the ground motion, or the presence of directivity pulses affect the distribution of maximum absolute sliding response, or can we just work with ordinary ground motions? In this case, it is not a structural treatment that we are after, but rather a ground motion based one. It is precisely the case where we do not have paired samples and we need to invent them. In this, we employ the short/long duration spectral twins of Chandramohan et al. (2016, 2020), and the pulse/no-pulse spectral twins of Kohrangi et al. (2019). As we are after the ensemble distribution, we turn directly to a Level 4 approach, resulting to the IDA fractile curves of Figure 10 for a given value of the friction coefficient. Quite clearly, the presence of pulses is of little consequence, as long as one accounts for the spectral shape and maintains the same PGA. On the contrary, ignoring the duration of ground motions will clearly bias the distribution median, regardless of maintaining the same spectral shape and PGA value. This has non-negligible implications. Essentially it means that one cannot create a prediction model for sliding response using ordinary ground motions and then try to apply it to a site influenced by a subduction zone; using it in the near field, though, should be fine.

A NeverEnding Story

Earthquake engineers will always seek to understand the deeper nature of structural response, researching new systems and revisiting conventional ones. Driven by curiosity, but also constrained by limited resources, they will venture into the Upside Down world of ground motions and seismology to figure out what matters and what does not. In this, paired sample testing is a valuable resource that can be applied at different levels of detail and help single out influential parameters, or more importantly, influential parameters under given site, intensity range, intensity measure type, ground motion type, structural system, level of response, and so on and so forth. Most importantly, statements that may not hold to scrutiny at the single ground motion level of detail, may become quite tenable if we only enlarge our view to encompass an ensemble of records.

In the end, perhaps the one thing to take home from this exercise is that simple monocausal explanations have been mostly researched out of earthquake engineering. If there are any left, they must be hiding exceptionally well, because all that is left out there is multiple factors that influence the response of our structures, each in its own intricate way. Mapping them out is best done with careful statistics, preferably exercised on paired samples.

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End Credits

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