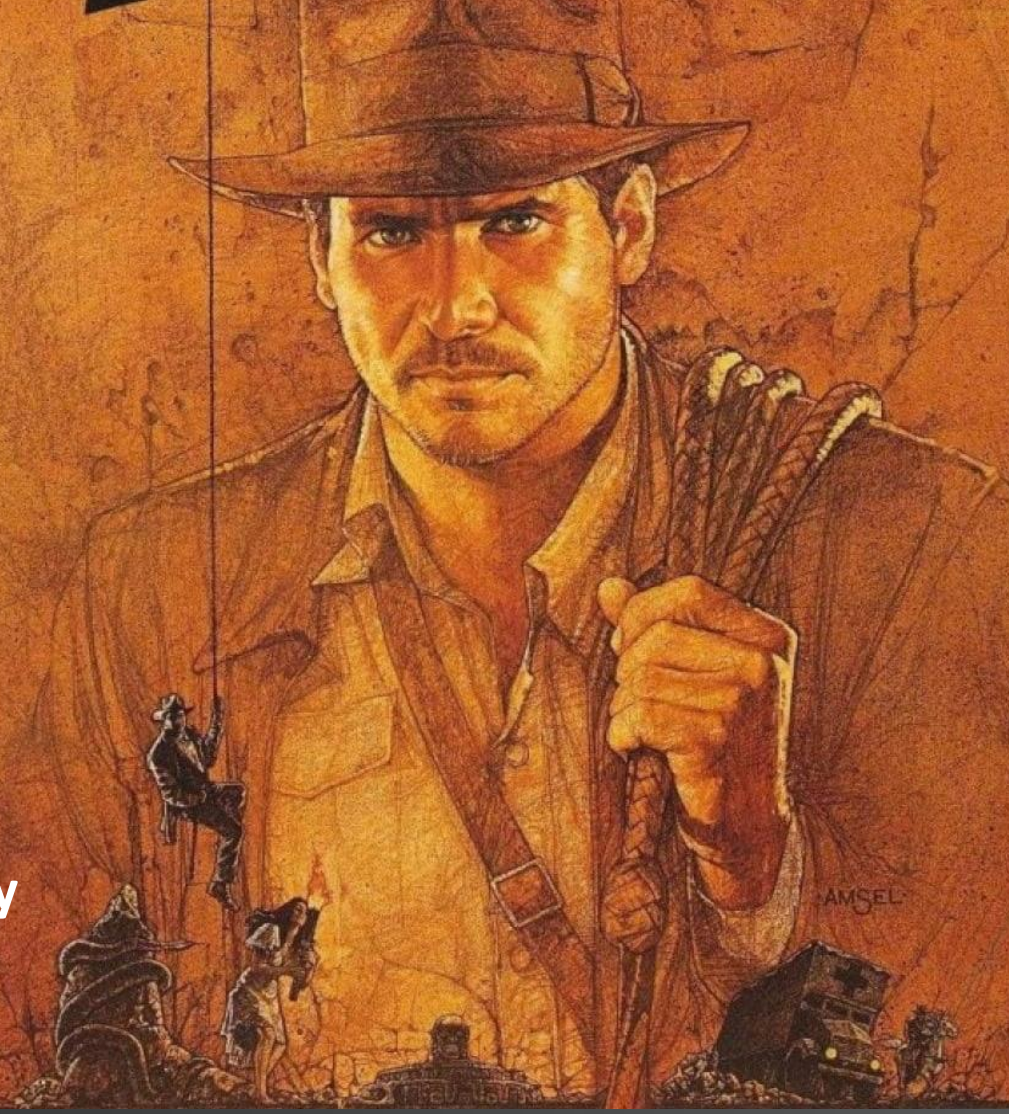
TOMB RAIDERS of the LOST ~~ARK~~ ACCELEROGRAM: A FRESH LOOK ON A STALE PROBLEM



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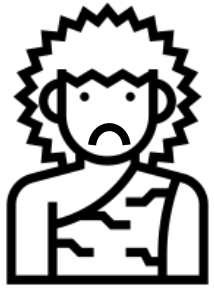
Bucharest, 9 September 2022

At the dawn of civilization

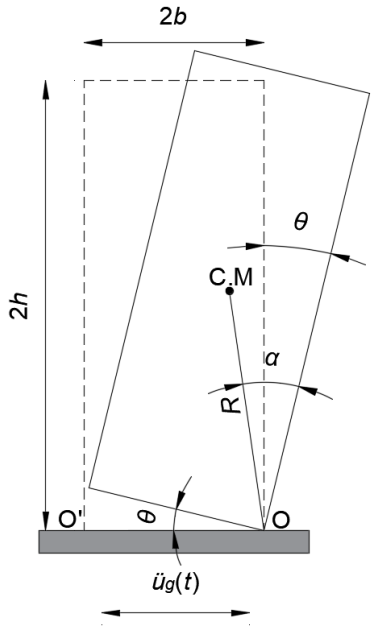
- It all started ~20,000 BC
- **Pottery** was invented

- ……so was **overturning**



- Someone was seriously unhappy
- Yet, the idea was planted.
- **Rigid bodies rock**

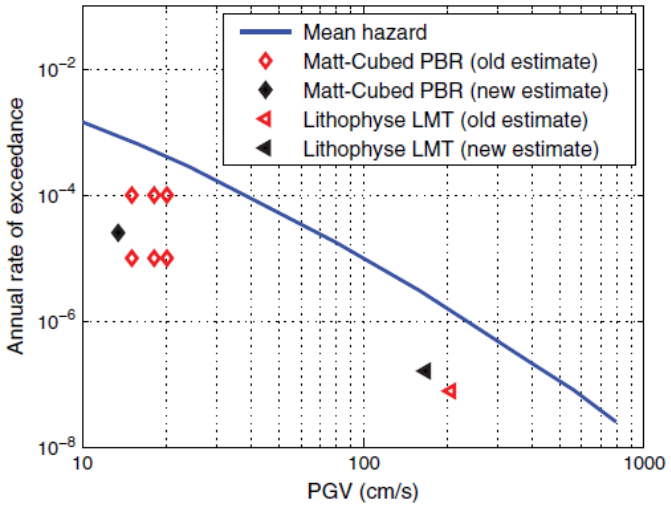
Civil engineers got it first!



- Prof. N. Mononobe, Japan (~1930s)
- **Overturning** associated with **seismic intensity**
- For 100+ years, Japanese engineers have gone **tomb raiding**
- Multiple observations and reports on overturned **tombstones**
- Housner got the **model** right (~1960s)
- ……but seismologists went one **step further**

Precarious rocks

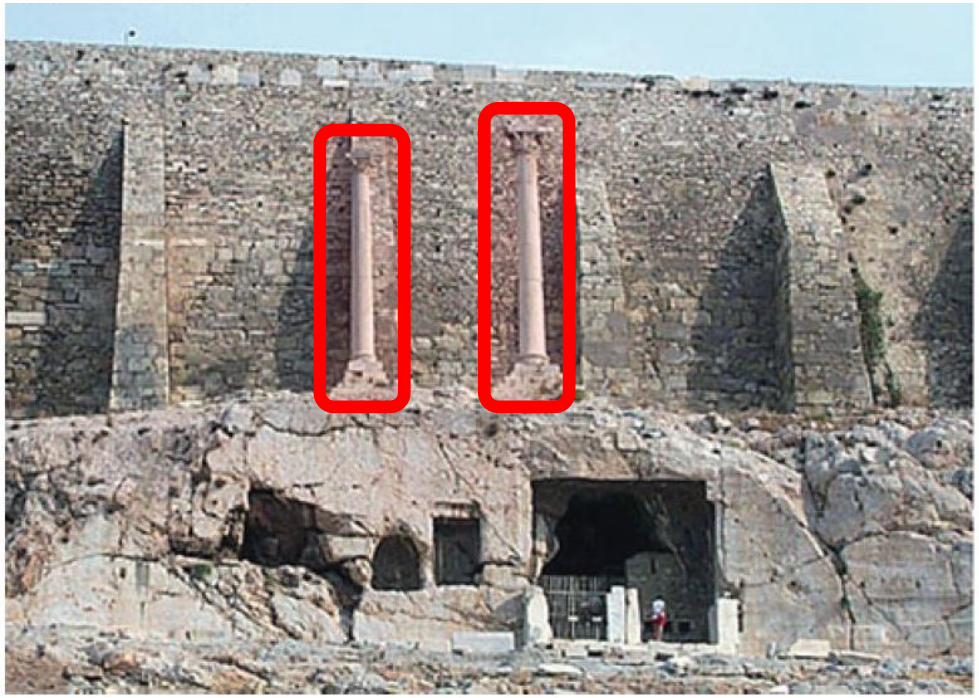
- Precarious rocks & fragile geological features
- **Used since 1994** to set bounds on ground motions

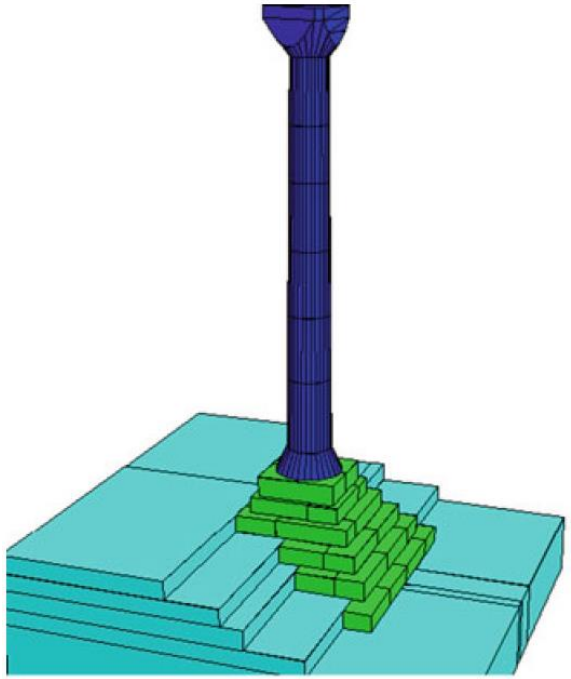


- Fully probabilistic approaches
- Used to **directly constrain** PSHA results!
- **GRRRRR!**

Image Credits: Baker et al (BSSA 2013)

Civil engineers still fighting back

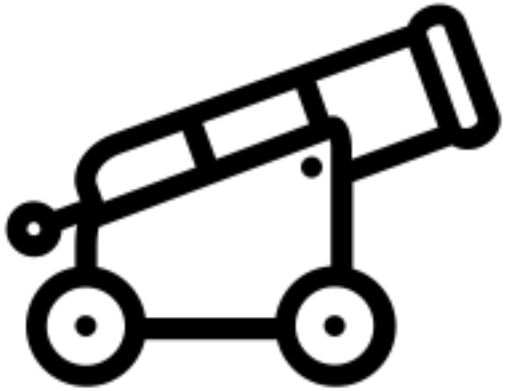




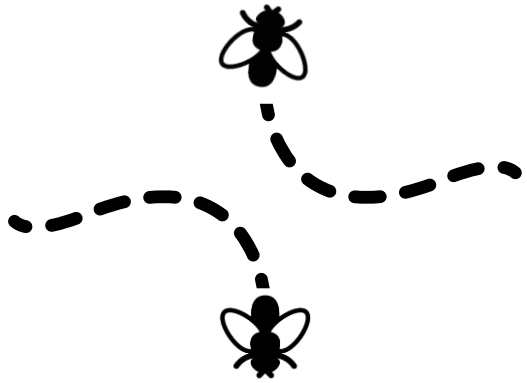
- Monument of **Thrasyllos**
- Two columns still standing after 2300yrs
- Ambraseys & Psycharis (2013)

- Modeling is key
- Conclusion: PGV<35cm/s with 2300yrs return period
- Can we do better?
- A bit **more probability** perhaps?

PBEE is here!

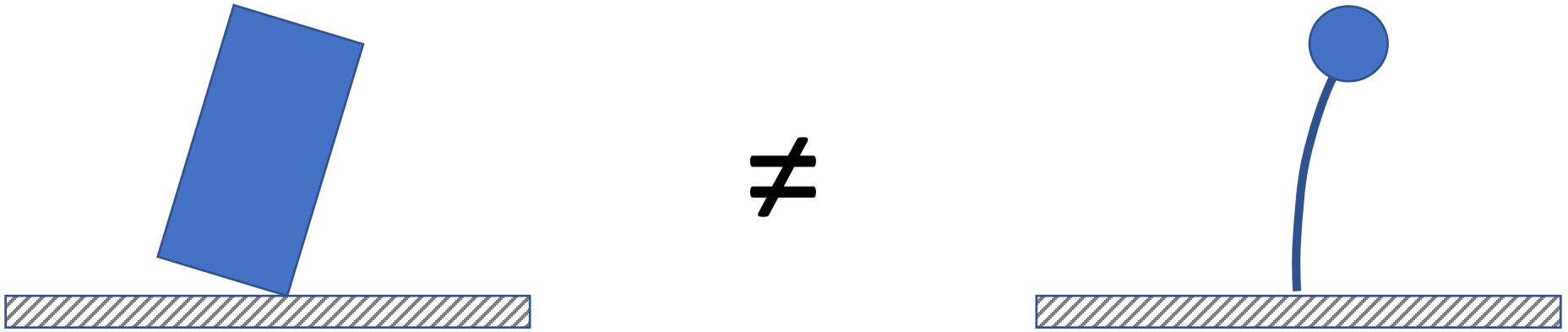


- We have GMPEs, fragities
- hazard, risk
- performance-based cannon!



- Let’s use our PBEE cannon to fire at the tombstone problem
- Hit or miss, it will be **fun**!
- …although not necessarily **useful**

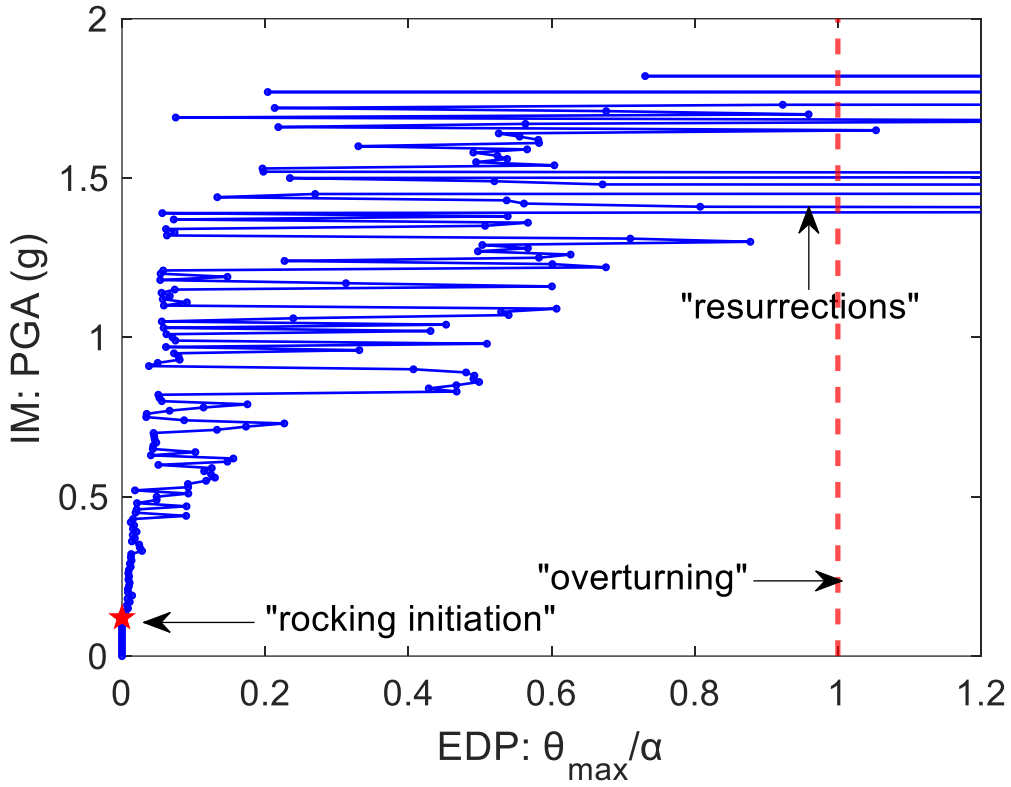
To do so, we need some help



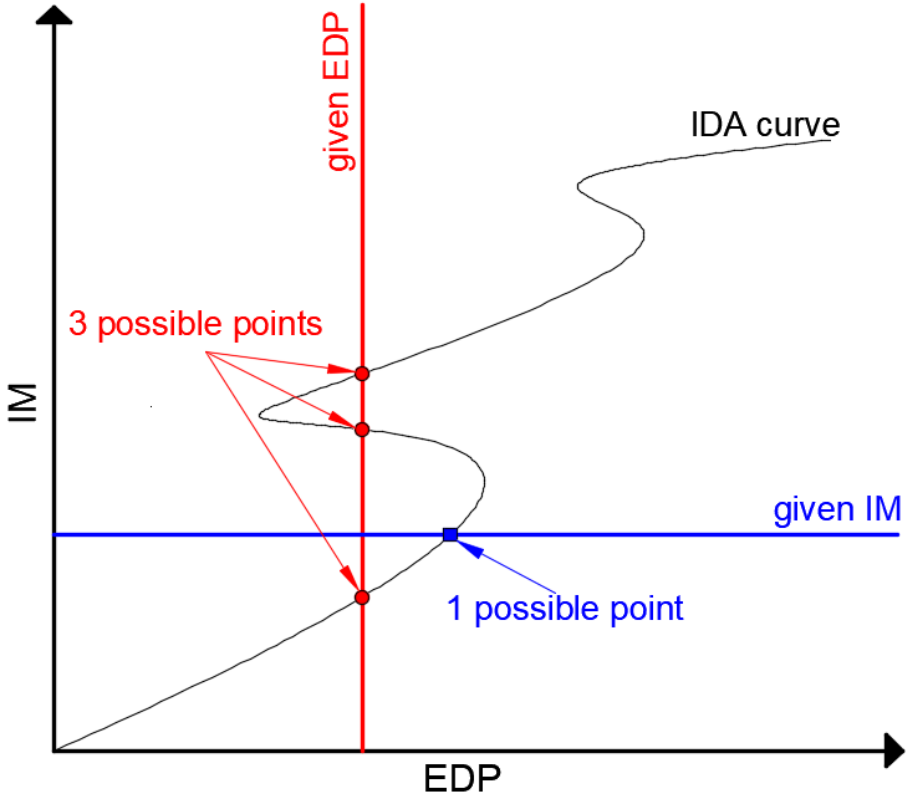
- Rocking is **not** very probabilistic at heart
- Sensitive to modeling, initial conditions, impact simulation, etc.
- Focus was on understanding & fixing
- A lot of "standard" PBEE stuff has **not been translated** to rocking

- We are missing **standardized** fragilities
- Probabilistic treatment of **parameter** influence
- **IM** optimality
- Even **IDA** postprocessing ☹
- **Indiana goes nowhere without tools!**

Issue #1: Rocking IDAs are weird!



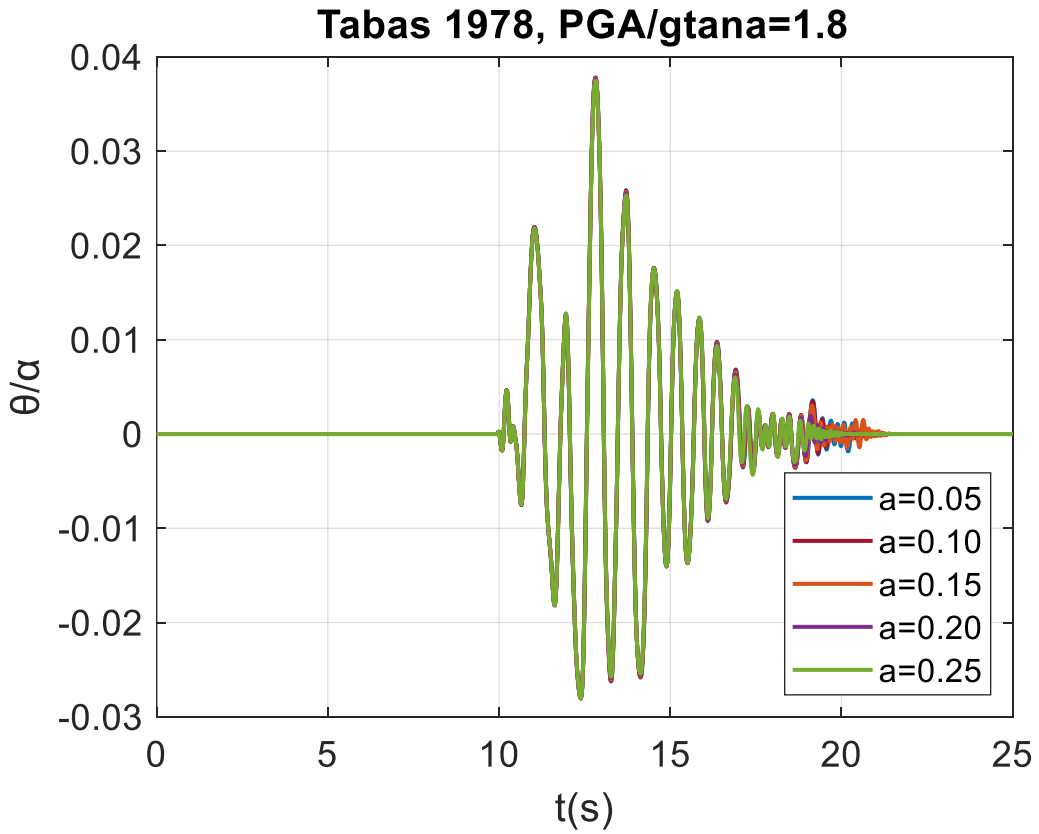
How you run & postprocess will affect the results



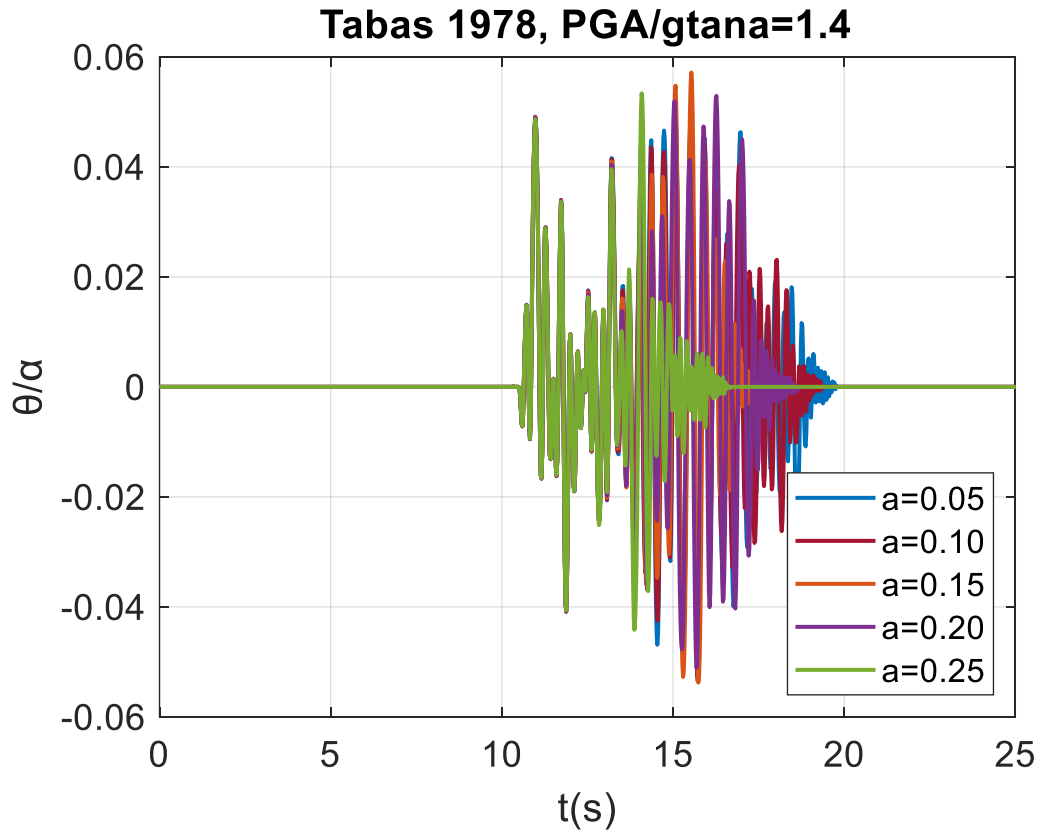
When in doubt, choose the middle!

Lachanas C.G., Vamvatsikos D. (2022). Rocking incremental dynamic analysis. Earthquake Engineering and Structural Dynamics, DOI:10.1002/eqe.3586

Issue #2: Does the shape of the block matter?



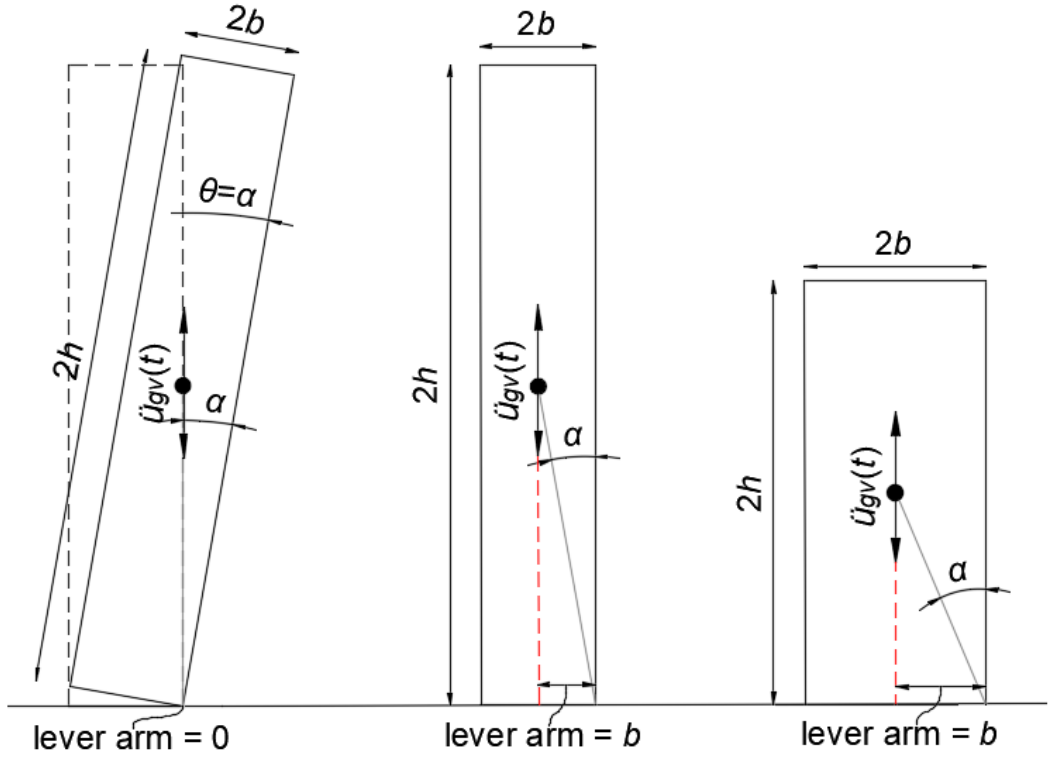
No it does not for p = $1s^{-1}$



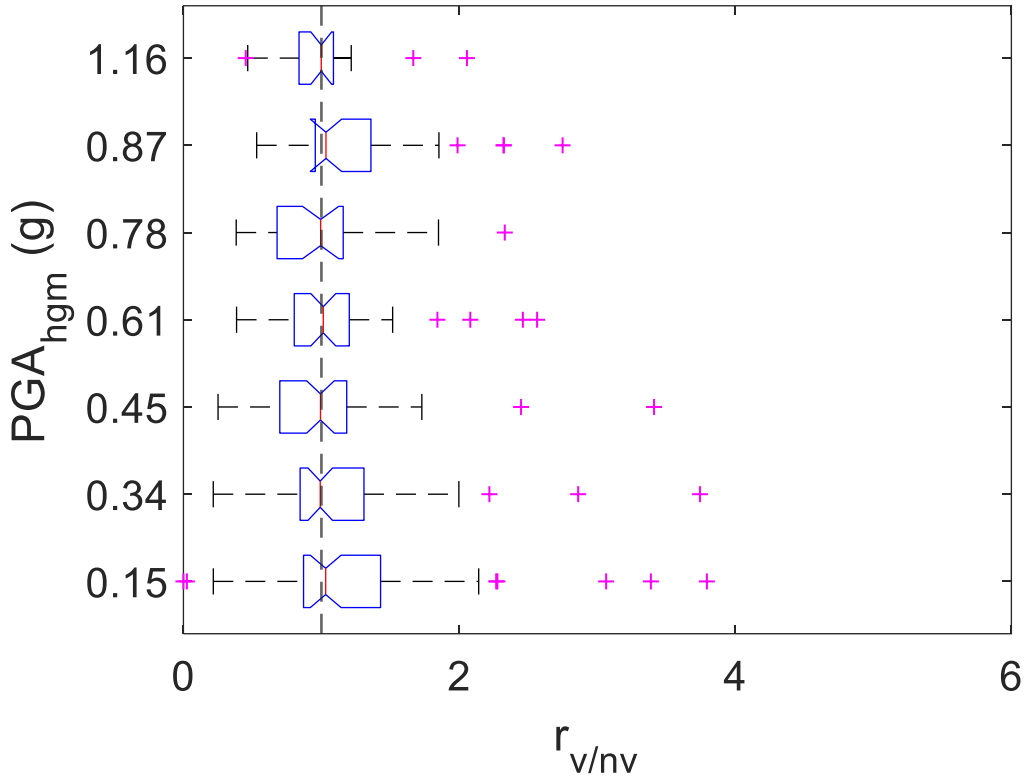
Yes it does for p = $3s^{-1}$
But does it really?

Lachanas C.G., Vamvatsikos D., Dimitrakopoulos E.G. (2023). Statistical properties of simple rocking block response (pending)

Issue #3: Does the vertical component matter?



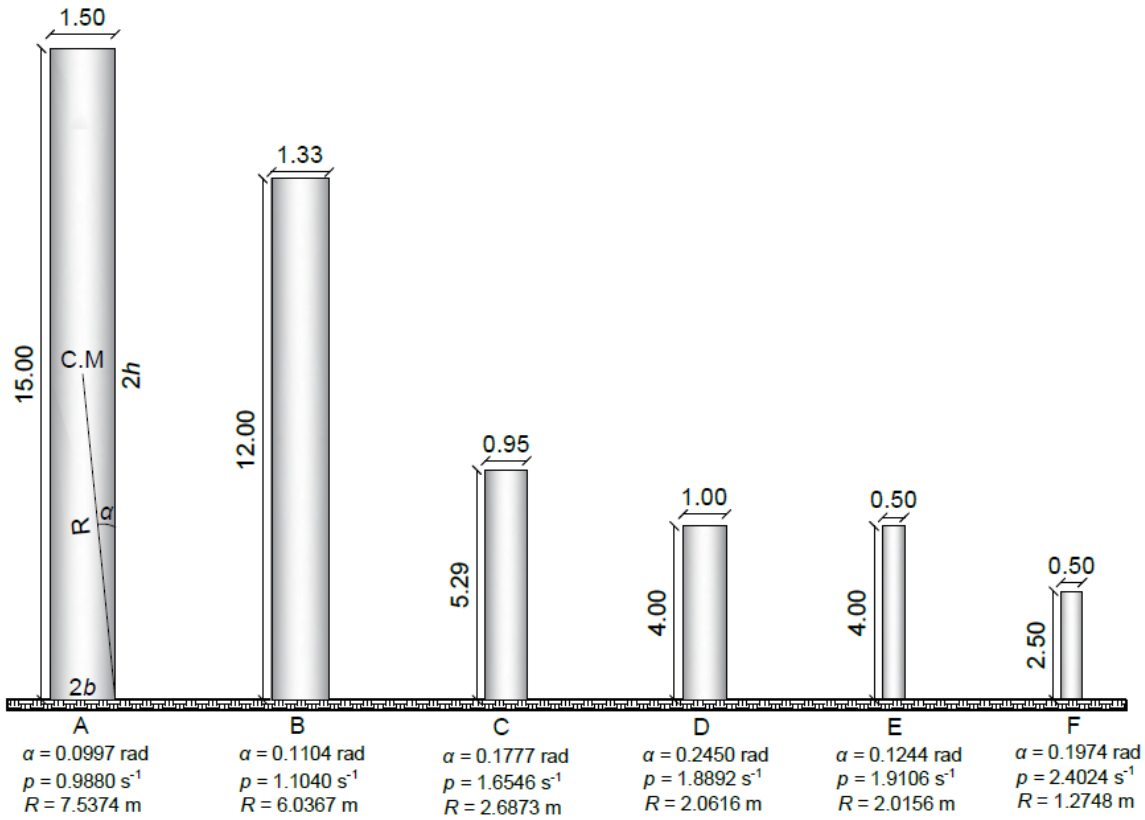
Only for rocking initiation of stocky blocks (ask Makris et al)

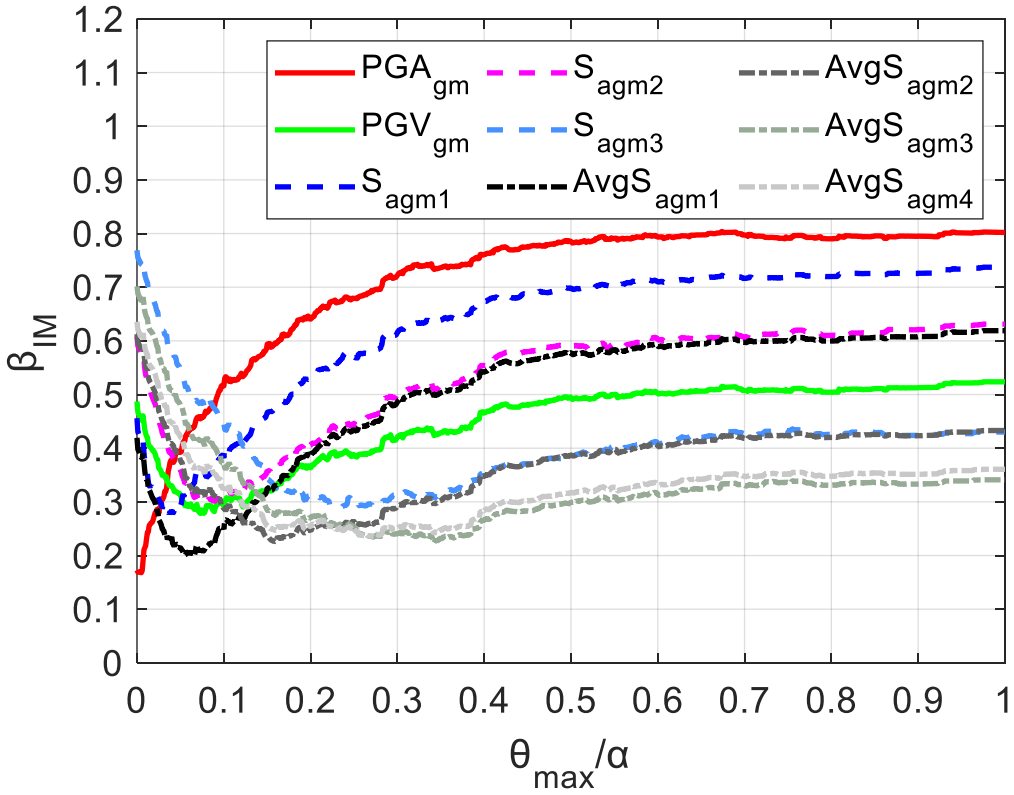


In general, with/without vertical makes no difference

Lachanas C.G., Vamvatsikos D., Vassiliou M.F. (2022). The influence of the vertical component of ground motion on the probabilistic treatment of the rocking response of free-standing blocks. DOI:10.1002/eqe.3643

Issue #4: Which intensity measure to use?





Onset -> PGA

Overturning -> AvgSa or maybe PGV

Lachanas C.G., Vamvatsikos D., Dimitrakopoulos E.G. (2022). Intensity measures as interface variables versus response proxies: the case of rigid rocking blocks (pending)

Issue #5: What is a good surrogate model for overturning?

Central value

$$\tilde{\theta}_{50}(I_A) = \begin{cases} \tilde{\theta}_1 \, (I_A - C_1)/(1.2 - C_1) & \text{for } C_1 \le I_A \le 1.2 \\ 0.1A_1(I_A - C_1)^{1.25} - \dfrac{B_1}{100} & \text{for } 1.2 < I_A < I_{A50,ovt} \\ 1 & \text{for } I_A \ge I_{A50,ovt} \end{cases}$$

$$I_{A50}(\tilde{\theta}) = \begin{cases} C_1 + (1.2 - C_1)\,\tilde{\theta}/\tilde{\theta}_1 & \text{for } 0 \le \tilde{\theta} \le \tilde{\theta}_1 \\ \left(\dfrac{\tilde{\theta} + \dfrac{B_1}{100}}{0.1A_1}\right)^{\frac{1}{1.25}} + C_1 & \text{for } \tilde{\theta}_1 < \tilde{\theta} < 1 \\ I_{A50,ovt} & \text{for } \tilde{\theta} \ge 1 \end{cases}$$

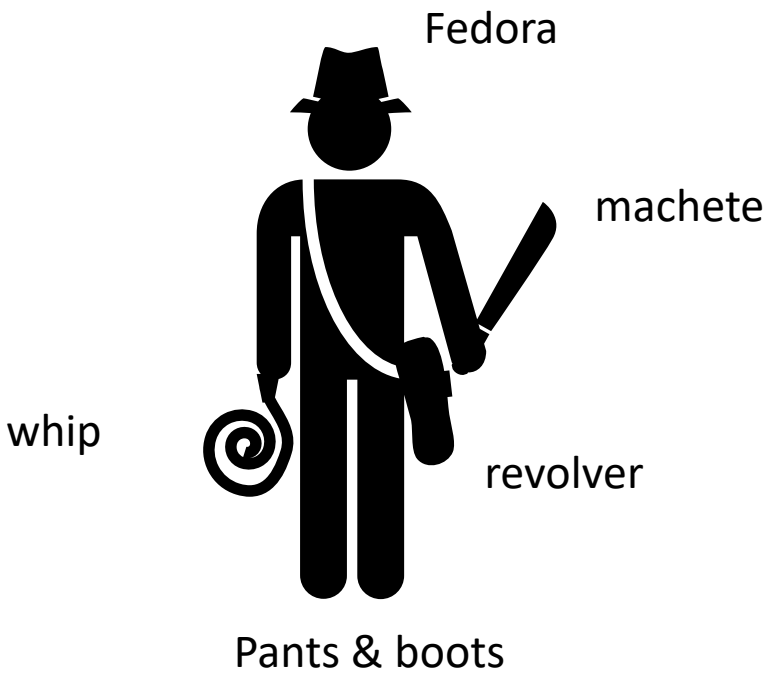
$$I_{A50,ovt} = A_2 + \frac{B_2}{p^2}$$

Dispersion (given EDP)

$$\beta_A(\tilde{\theta}) = \begin{cases} A_1 \dfrac{\tilde{\theta}^{B_1}}{e^{\tilde{\theta}}} + C_1 & \text{for } 0 \le \tilde{\theta} \le 0.8 \\ \beta_A(\tilde{\theta} = 0.8) & \text{elsewhere} \end{cases}$$

Kazantzi A.K., Lachanas C.G., Vamvatsikos D. (2021). Seismic response distribution expressions for on-ground rigid rocking blocks under ordinary ground motions. DOI: 10.1002/eqe.3511

Ready to roll?



- Indiana Jones is now tooled up
- Let us go raiding for the lost accelerogram!

What are we looking for?

$$\mathrm{P}(\mathrm{O} \mid PGV = x)$$

- Probability of overturn **given IM**
- This is the **fragility**!
- We have it thanks to Kazantzi et al.

$$\mathrm{P}(PGV = x \mid \mathrm{O})$$

- Probability of IM **given overturn**
- This is what we want
- How to get it?
- Invert conditioning -> **Bayes**

Just Bayes rule, but how?

PDF of PGV given overturning

Overturning fragility

?

$$P(PGV = x \mid O) = \frac{P(O \mid PGV = x)\, P(PGV = x)}{P(O)}$$

?

- Two terms are just meaningless
- ……but they provide a clue
- **Cannot estimate** P(PGV=x) without info on **event**

Just Bayes rule, properly applied

PDF of PGV given overturning and event

Overturning fragility

GMPE

$$\mathrm{P}(PGV = x \mid \mathrm{O}, MR) = \frac{\mathrm{P}(\mathrm{O} \mid PGV = x, MR)\ \mathrm{P}(PGV = x \mid MR)}{\mathrm{P}(\mathrm{O} \mid MR)}$$

Overturning risk given the event

- MR = Magnitude, Distance, site, etc.

Just Bayes rule, expanded & simplified

PDF of PGV given overturning and event

Overturning fragility (no MR!)

GMPE

$$\mathrm{P}(PGV = x \mid \mathrm{O}, MR) = \frac{\mathrm{P}(\mathrm{O} \mid PGV = x) \cdot \mathrm{P}(PGV = x \mid MR)}{\int_{x'=0}^{x'=\infty} \mathrm{P}(\mathrm{O} \mid PGV = x') \cdot \mathrm{P}(PGV = x' \mid MR)\, \mathrm{d}x'}$$

Overturning risk given the event

- If you need the PDF **given survival**, just replace one term (which?)

To truncate or not to truncate?

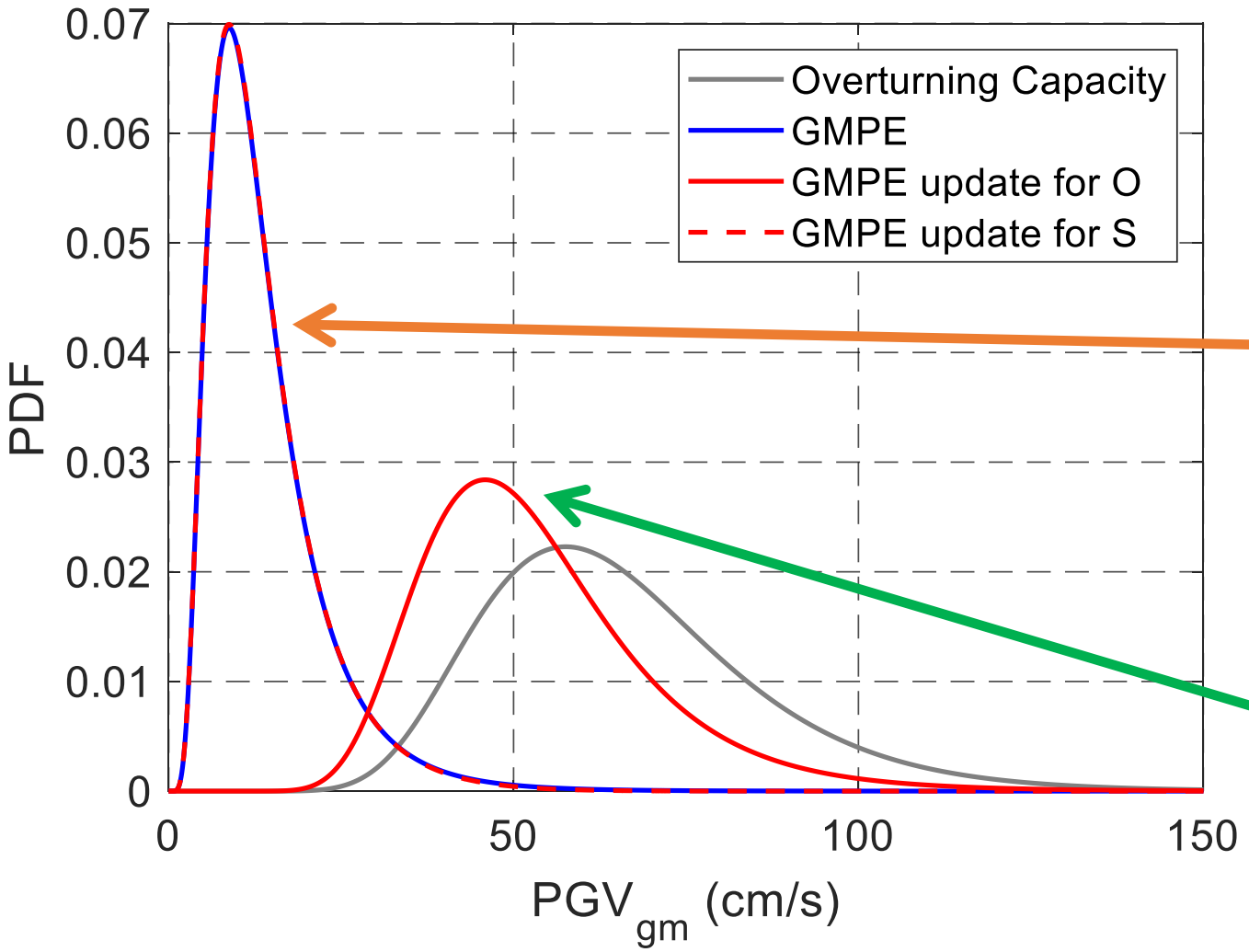
- **Lognormals** are everywhere: GMPEs & fragilities
  - bounded by **zero** on the left
  - ……but **no bound** on the right

- Models of blocks & motions are **imperfect**
  - Not bounding excessive predictions -> everything is possible!
  - M=6 can produce PGV = 20m/s? **P>0**!
  - Apply e.g. **$\pm 3\sigma_{ln}$ truncation** to restore sanity

Single block example

- Assume a single rigid block
  - b/h = 0.2, p = $2s^{-1}$
  - Overturning at median PGV≈0.63m/s, β ≈ 0.3
  - Not exactly easy to overturn
- Two events
  - **M=6** and **M=8** on reverse fault
  - R_{JB} = 10km
  - GMPE of Boore and Atkinson (2008)
  - v_{s30} = 400m/s

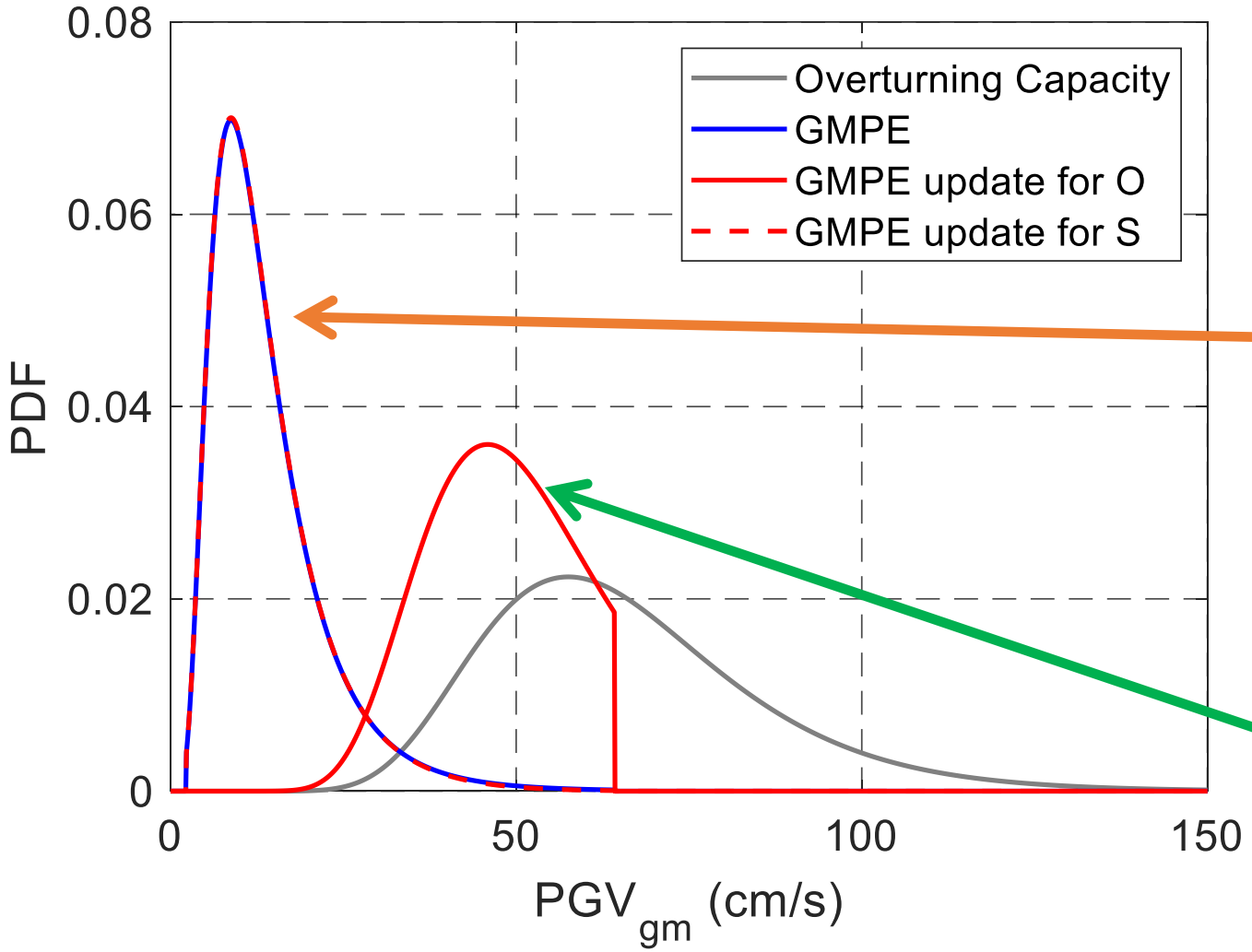
Single block, M=6 no truncation



Survive = no info
(small event, no damage on sturdy block, so what?)

Overturn = useful
(small event with damage, cool!)

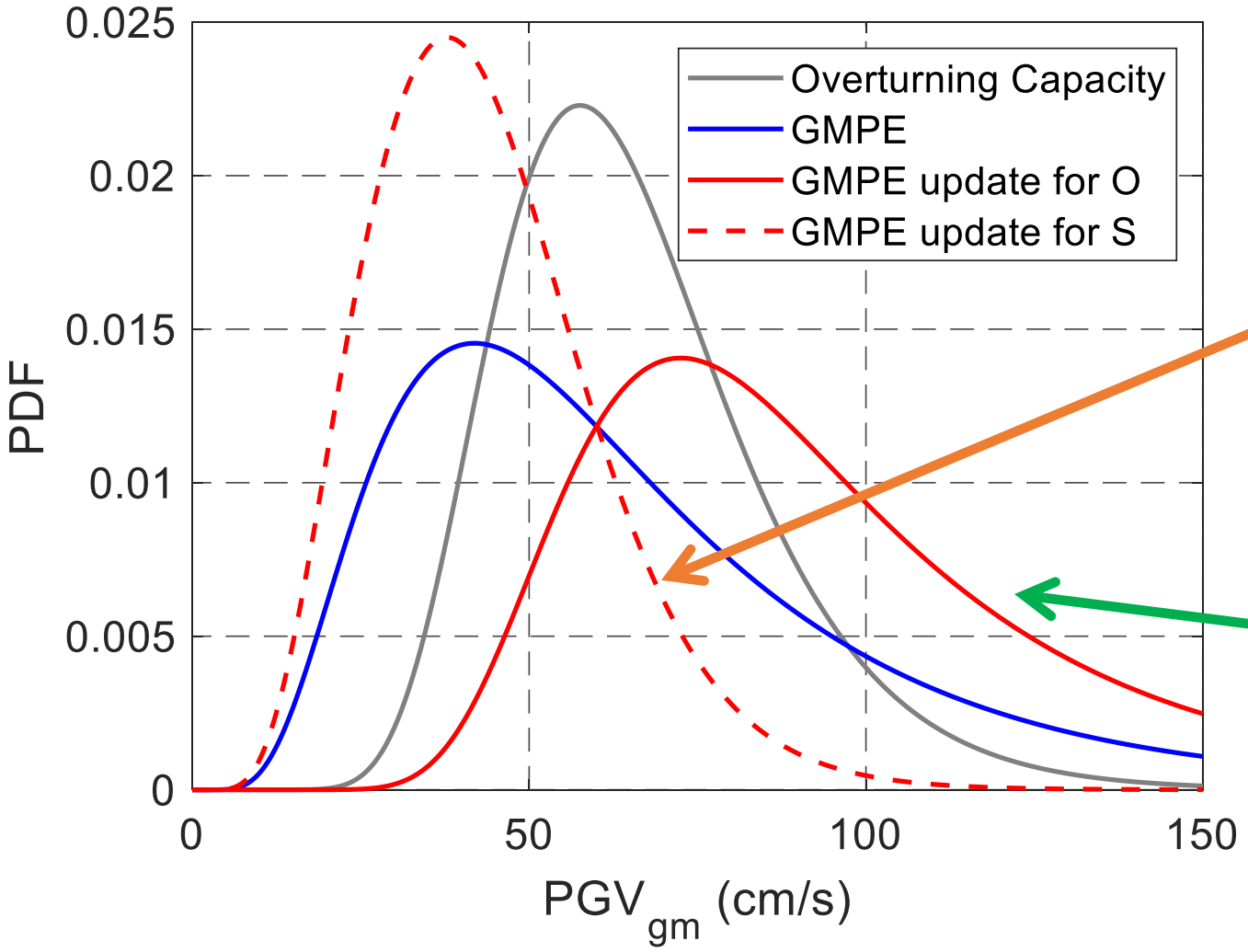
Single block, M=6 with truncation



Survive = no info
(small event, no damage on sturdy block, so what?)

Overturn = useful
(small event with damage and GMPE cutoff, really cool!)

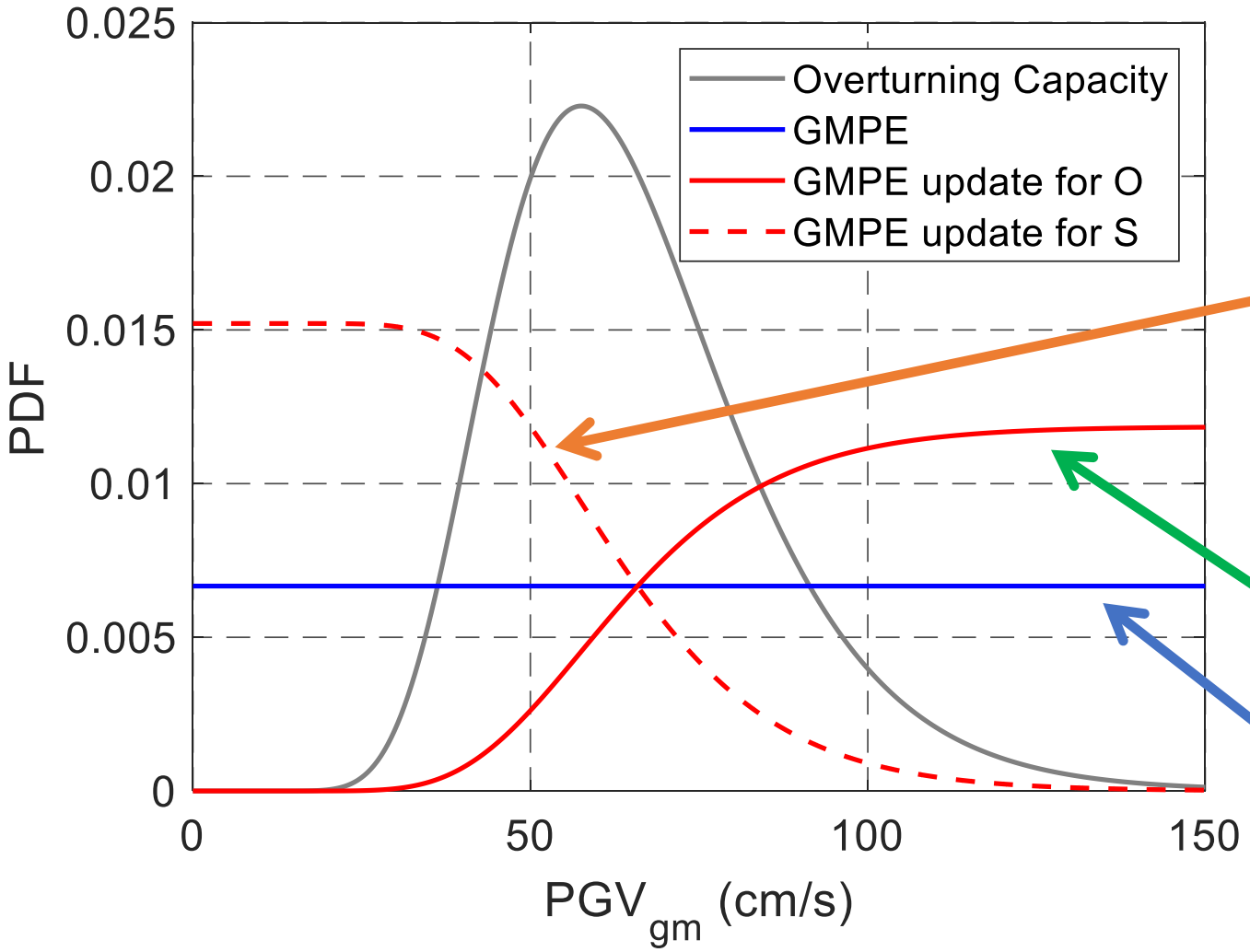
Single block, M=8



Survive = good info!
(big event, no damage on sturdy block, hmmm)

Overturn = ok info!
(big event with damage, not bad)

Single block, M=?



Survive = upper bound
(no damage on sturdy block)

Overturn = lower bound
(overturned sturdy block)

Uninformative prior for GMPE

At last, the graveyard

- What if we had a graveyard of **identical** tombstones?
  - b/h = 0.2, p = $2s^{-1}$
  - Overturning at median PGV≈0.63m/s, β ≈ 0.3

- Should they not behave **identically**?
  - Have you ever tried to **replicate** rocking tests?
  - ……does not work as well
  - Little details make a huge difference
  - Say r_1 overturn, and 1 – r_1 do not

Use a simple logic tree

r_1 — Overturn

$1 - r_1$ — Survive

PDF of PGV given some overturning and event

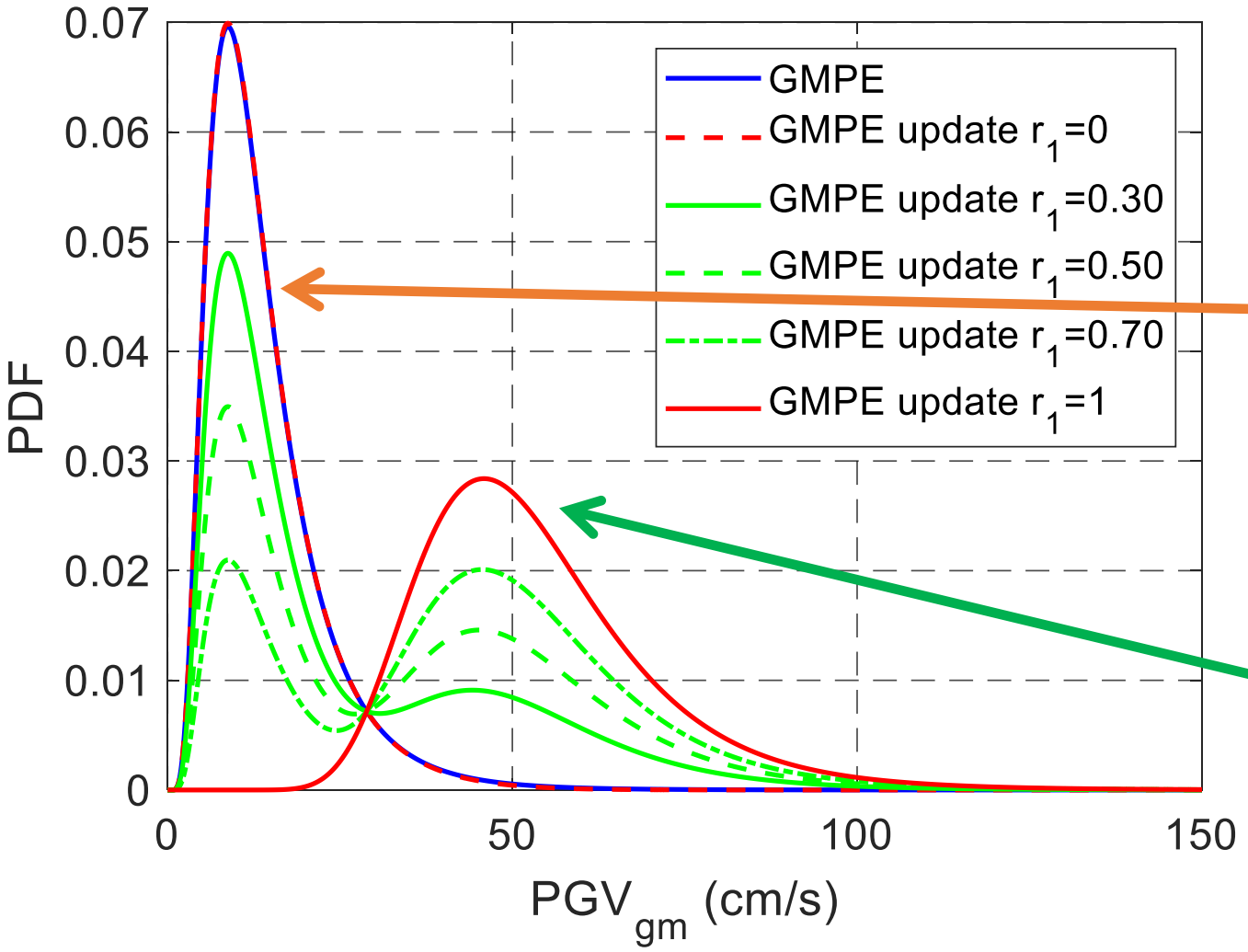
PDF given overturn

PDF given survival

$$\mathrm{P}(PGV = x \mid r_1, MR) = r_1 \cdot \mathrm{P}(PGV = x \mid \mathrm{O}, MR) + (1 - r_1) \cdot \mathrm{P}(PGV = x \mid \mathrm{S}, MR)$$

Observation weights

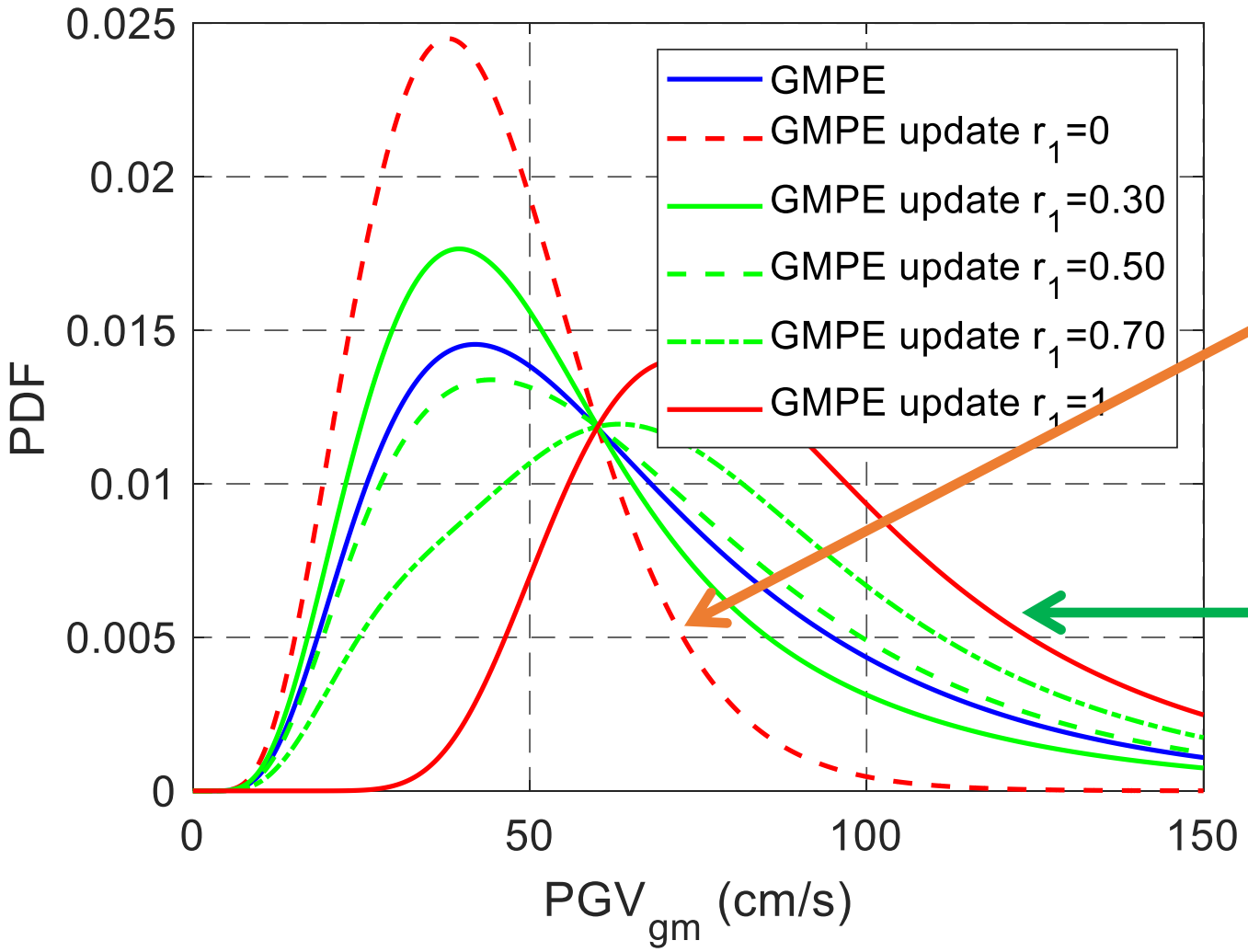
Single graveyard, M=6



All survive = no info
(small event, no damage on sturdy block, so what?)

All overturn = useful
(small event with damage, cool!)

Single graveyard, M=8



Survive = good info!
(big event, no damage on sturdy block, hmmm)

Overturn = ok info!
(big event with damage, not bad)

To infinity and beyond!

What about a graveyard of **non-identical** tombstones?

That is the dream!

"Weakest" one to **survive** gives tight lower bound

"Sturdiest" one to **overturn** gives tight upper bound

...but uncertainty may ruin all...

Until the paper comes out, let's do some **art**

The Forever Seismic Art project

Acknowledgements

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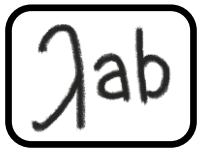
  - www.hyperion-project.eu twincity.ntua.gr/
- Friends, collaborators, postdocs και PhD students of the 

(lambdalab.ntua.gr)
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