International Symposium
Qualification of dynamic analyses of dams and their equipments
and of probabilistic assessment seismic hazard in Europe
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Session 3: Soils properties and simplified analysis

SIMPLIFIED ANALYTICAL RELATIONSHIPS FOR SEISMICALLY INDUCED SLOPE DISPLACEMENTS

SUMMARY

1. **Assessment of earthquake induced slope displacements using nonlinear finite difference parametric dynamic analysis for different slope geometries, soil properties and input motion**

2. **Proposition of new displacement predictive models, alternative of Newmark type models, which relate the co-seismic slope displacement with the best correlated parameters characterizing the intensity of the strong ground motion**

3. **Comparison of the numerical results in terms of co-seismic permanent slope displacements with empirical Newmark-type displacement based models and**

4. **Examples**

Earthquake triggered landslides

- **Around 20% of the registered landslides are triggered by earthquakes** (*Wen et al., 2004*)
- **Landslides are both the most abundant and the most deadly earthquake-induced secondary effect, being responsible for 71.1% of the non-shaking deaths** (*Marano et al., 2010*)

Seismic performance of embankment dams

- **Historically, few dams have been significantly damaged by earthquakes**
- **Hydraulic fill dams and tailings dams represent the most hazardous types of embankment dams**
- **Rockfill dams or concrete face rockfill dams (CFRD's) represent desirable types of dams in highly seismic areas *(USSD 2014)***

Niigata–Ken Chuetsu 2004 earthquake effects on embankment dams *(Yasuda et al. 2004)*

Stepping caused by crest cracking (Asagawara Regulating Reservoir)

Slip of reservoir side slope (Yamamoto Regulating Reservoir)

Crack on downstream slope (Tsuboyama Dam)

Seismic analysis of embankment dams (ICOLD, 2016)

- Seismic analyses using the **Newmark method** or **detailed linear or nonlinear dynamic finite element and finite difference procedures**
- **Simplified procedures (e.g. Newmark-type) should always be attempted before using more detailed and complex methods** although it is noted that pseudostatic analyses cannot be relied upon to give a realistic evaluation
- If the **foundation and embankment materials not susceptible to loss of strength and stiffness** (e.g., liquefaction) and if the **embankment not saturated**, the **dynamic analysis of the dam** will serve as a basis to **estimate permanent earthquake-induced displacements using the methods of Newmark or others**
- If the foundation or embankment materials **can lose stiffness and strength**, a **dynamic analysis of the dam** should be used to determine whether the **earthquake-induced stresses are sufficient to trigger a loss of strength**

Seismic analysis of embankment dams ICOLD 2016

Appropriate seismic input for the simplified methods to assess permanent earthquake-induced displacements:

Acceleration time histories, spectral accelerations or peak ground acceleration (PGA) at bedrock developed by either a Deterministic Seismic Hazard Analysis (DSHA) or a Probabilistic Seismic Hazard Approach (PSHA) (e.g. SHARE European project) for the safety evaluation earthquake (SEE) and Operating Basis Earthquake (OBE) conditions *(ICOLD, 2016)*

Definition of IMs (PHGA, PVGA, PGV, PSA etc) at any point of interest given the corresponding parameters at the rock outcrop applying either full dynamic 2D and 3D analysis of the dam or simplified approaches

Outline

Simplified analysis for the evaluation of the permanent slope displacements using appropriate IMs (PGA, PGV, PSA etc)

Definition of IMs at the depth of the sliding surface given the corresponding parameters of the design ground motion (OBE or SEE) at the rock outcrop using (i) a Probabilistic Seismic Hazard Assessment (PSHA) and (ii) seismic amplification and aggravation factors proposed in the previous presentation *(Pitilakis and Riga 2016)*

No liquefaction and associated effects are considered

Fotopoulou S, Pitilakis K (2015) Predictive relationships for seismically induced slope displacements using numerical analysis results. Bulletin of Earthquake Engineering, DOI 10.1007/s10518-015-9768-4.

Earthquake induced landslide hazard

- **Likelihood or probability of occurrence of a landslide → frequency of seismically induced landslides**
- **Factor of safety of a slope → pseudostatic approach**
- **Slope displacement along a slip surface → Newmark-type displacement methods & advanced stress-strain dynamic analysis**

Considering that permanent slope displacements ultimately govern the serviceability level of a slope after an earthquake and represent the main cause of damage to affected structures, ***the use of displacement-based approaches is strongly recommended***

Predictive models for co-seismic slope displacements

Two different approaches of increased complexity are proposed:

- **Newmark-type empirical displacement methods** based on the sliding block assumption first proposed by *Newmark (1965)*
- **Advanced numerical methods** based on continuum mechanics (finite element and finite difference methods) or discontinuum formulations

Both methodologies depend on the appropriate selection and evaluation of the input motion parameters (Intensity Measures, IMs) and the slope characteristics (geometry, soil properties)

Newmark type predictive models

Three main types of displacement-based methods to predict seismically induced permanent slope displacements:

- **Rigid block** (e.g. *Newmark 1965; Ambraseys and Menu 1988; Jibson 2007*, etc.)
- **Decoupled** (e.g. *Makdisi and Seed 1978; Bray and Rathje 1998, Rathje and Antonakos 2011* etc.)
- **Coupled** (e.g. *Bray and Travasarou 2007*)

Newmark type predictive models

Newmark (1965) analytical rigid block method

- Newmark's method treats the landslide as a **rigid plastic block**
- Known **yield or critical acceleration**
- **Cumulative displacements** estimated by double-integrating the parts of an acceleration-time history that lie above the critical acceleration
- Predicts **average (mean) slope displacements**

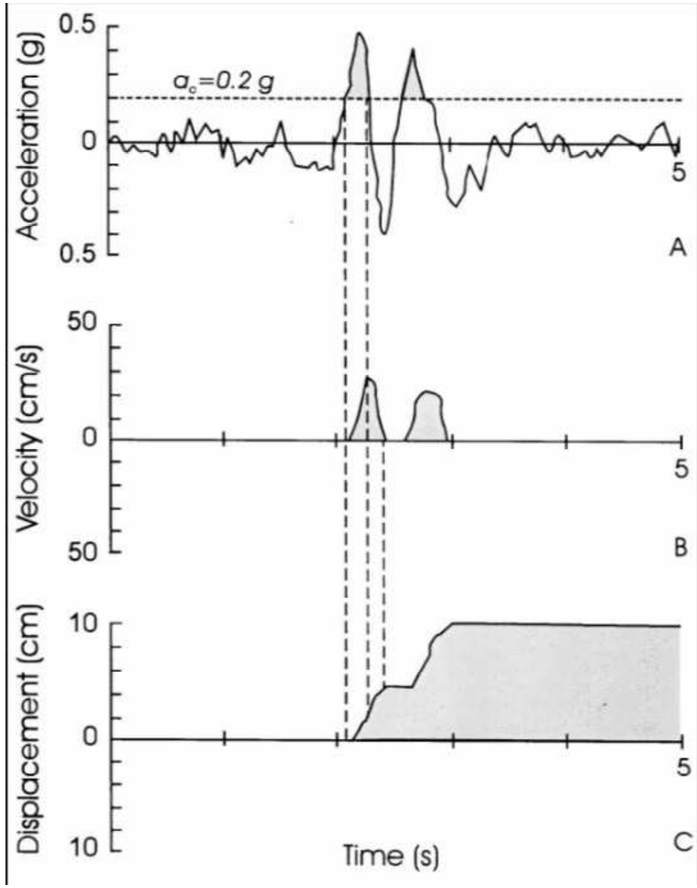


Illustration of the Newmark integration algorithm, adapted from Wilson and Keefer (1983)

Newmark type predictive models

Jibson (2007) rigid block model

- *Jibson (2007)* proposed four regression equations to predict Newmark **rigid block displacement** in terms of : (1) **critical acceleration ratio**, (2) **critical acceleration ratio and earthquake magnitude**, (3) **Arias intensity and critical acceleration** and (4) **Arias intensity and critical acceleration ratio**
- **Arias intensity** the most **efficient intensity measure** for **stiff, weak slopes** (*Travasarou 2003*)

Newmark type predictive models

Rathje and Antonakos (2011) decoupled model

Extension of *Saygili and Rathje (2008, 2009)* rigid-block displacement models for application to **flexible** sliding masses

Two vector (PGA, PGV) model to reduce the variability in the displacement prediction (*Saygili & Rathje 2008*)**:**

•$\mathbf{k_{max}}$ [$f(T_s/T_m)$]: peak value of the average acceleration time history within the sliding mass to replace **PGA** and

•**k-vel**$_{\mathbf{max}}$ [$f(T_s/T_m)$]: peak value of the k-vel time history provided by numerical integration of the k-time history to replace **PGV**

Newmark type predictive models

Bray and Travasarou (2007) coupled model

- **One-dimensional multi-degree of freedom non-linear coupled stick-slip model** (*Rathje and Bray 2000*)
- **S_a (1.5T_s)** is used to characterize the equivalent seismic loading on the sliding mass →the optimal IM in terms of efficiency and sufficiency (*Bray 2007*)
- Implementation within **a fully probabilistic framework**

Newmark type predictive models

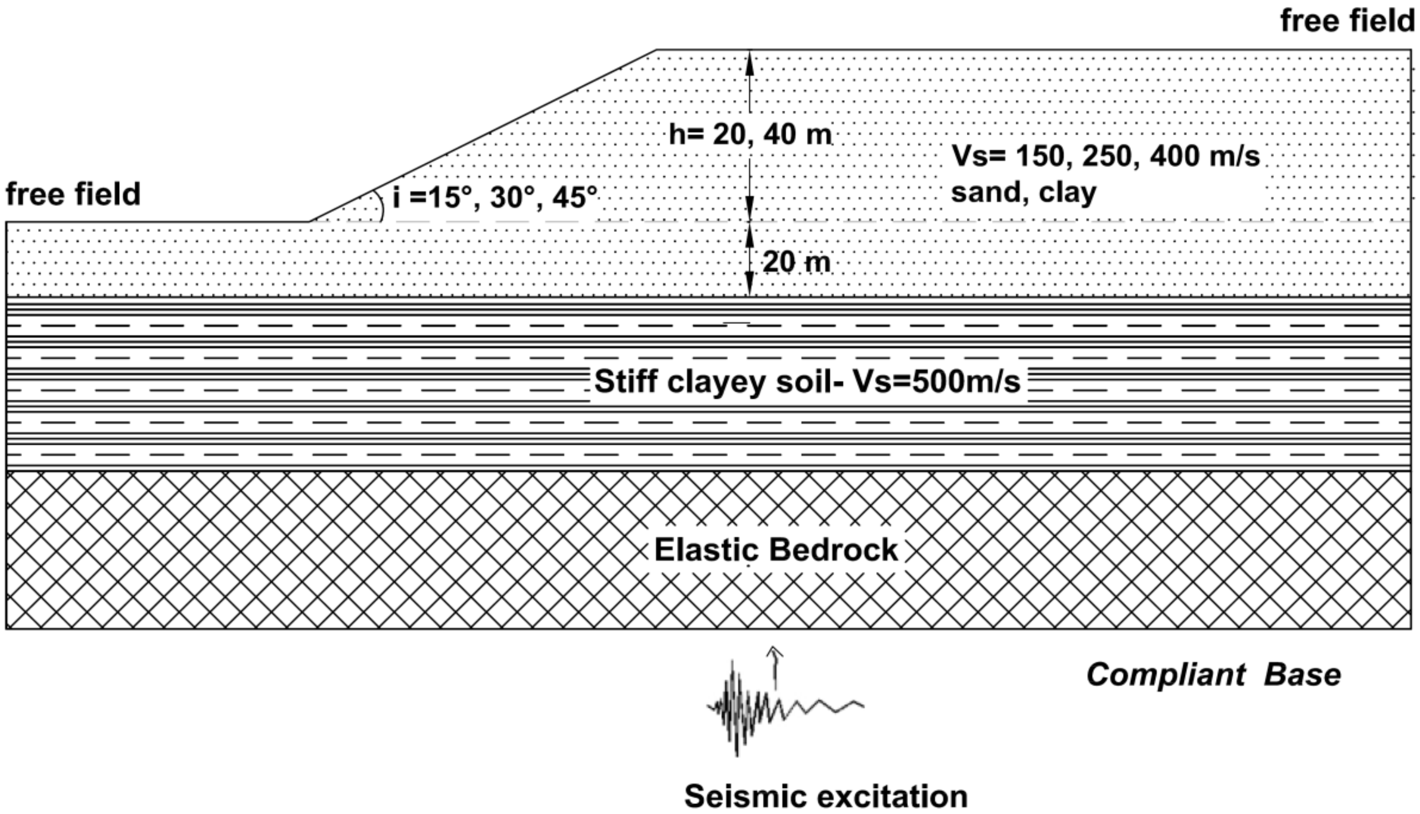
Model	Functional form
Jibson (2007) simplified rigid block model	$\log(D) = 0.561 \log(I_a) - 3.833 \log(a_c/PGA) - 1.474 \pm \sigma$ where D is in cm, I_a in m/s and PGA and a_c in g
Rathje and Antonakos (2011) simplified decoupled sliding block model	**For rigid sliding masses:** $\ln(D) = -1.56 - 4.58\left(\frac{k_y}{PGA}\right) - 20.84\left(\frac{k_y}{PGA}\right)^2 + 44.75\left(\frac{k_y}{PGA}\right)^3 - 30.50\left(\frac{k_y}{PGA}\right)^4 + -0.64\ln(PGA) + 1.55\ln(PGV) + \varepsilon\,\sigma_{\ln D}$ **For flexible sliding masses**, k_{max} and k-vel$_{max}$ are used to replace PGA and PGV respectively and a term conditioned to T_s is added: $\ln(D_{flexible}) = \ln(D_{PGA,PGV}) + 1.42T_s \quad \text{for } T_s \le 0.5$ $\ln(D_{flexible}) = \ln(D_{PGA,PGV}) + 0.71 \quad \text{for } T_s > 0.5$ where D and $D_{flexible}$ is in cm, PGA in g , PGV in cm/s and T_s in seconds
Bray and Travasarou (2007) simplified coupled stick-slip sliding block model	**For the flexible sliding block case (T_s>0.05):** $\ln(D) = -1.10 - 2.83\ln(k_y) - 0.333(\ln(k_y))^2 + 0.566\ln(k_y)\ln(S_a(1.5T_s)) + 3.04\ln(S_a(1.5T_s)) - 0.244(\ln(S_a(1.5T_s)))^2 + 1.50T_s + 0.278(M-7) \pm \varepsilon$ **For the nearly rigid sliding block case (T_s<0.05):** $\ln(D) = -0.22 - 2.83\ln(k_y) - 0.333(\ln(k_y))^2 + 0.566\ln(k_y)\ln(PGA) + 3.04\ln(PGA) - 0.244(\ln(PGA))^2 + 1.50T_s + 0.278(M-7) \pm \varepsilon$ where D is in cm, T_s in seconds and $S_a(1.5T_s)$ and PGA in g

Seismically induced slope displacements using numerical analysis

Numerical parametric analysis- Basic points

- **2D fully non-linear dynamic analysis**
- **Finite difference code FLAC2D** (*Itasca 2011*)
- **Free field absorbing boundaries along the lateral boundaries - quiet boundaries along the bottom**
- **Elastoplastic constitutive model - Mohr-Coulomb failure criterion**
- **Typical slope soil models**: varying geometrical characteristics, material properties of the surface layer, strength and stiffness of the sliding surface
- **Yield coefficient k_y= 0.05÷0.3 and fundamental period of the sliding mass T_s (T_s=4H/Vs) = 0.05÷0.69s**
- **Depth of the sliding surface (H) and k_y** : estimated by Bishop pseudostatic slope stability analysis
- **Input motion**: **40 real acceleration time histories** recorded on rock or very stiff soil (EC8) (*SHARE database*), Mw=5÷7.62 , R=3.4÷71.4 km, PGA= 0.065÷0.91g

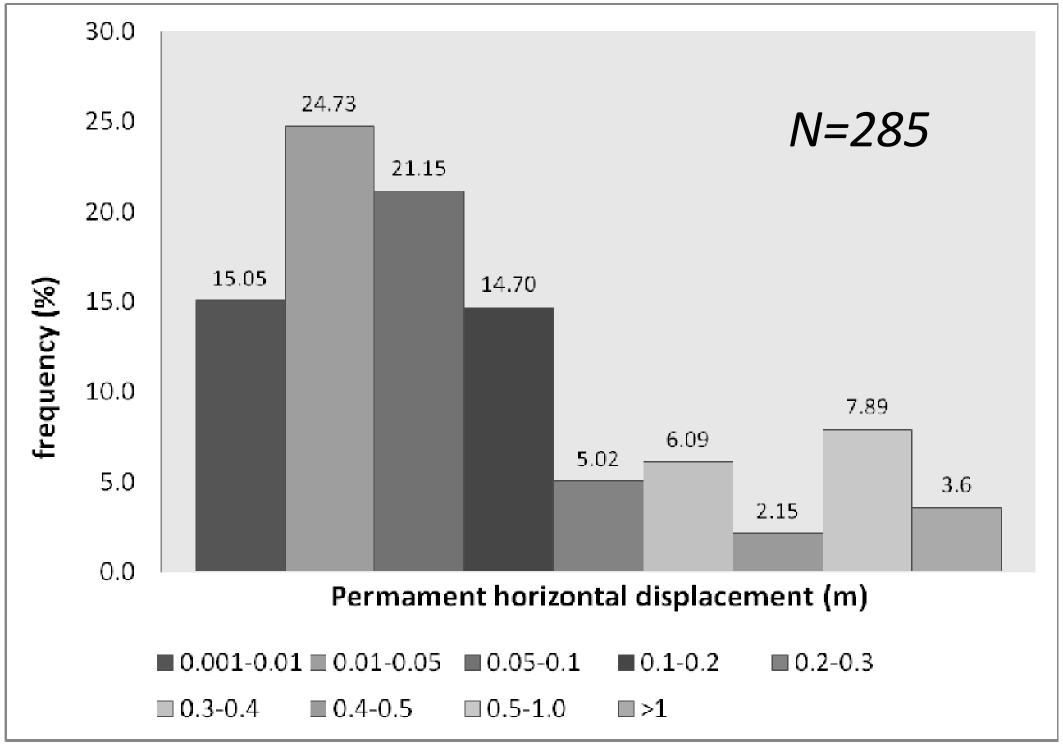
Seismically induced slope displacements using numerical analysis



Seismically induced slope displacements using numerical analysis

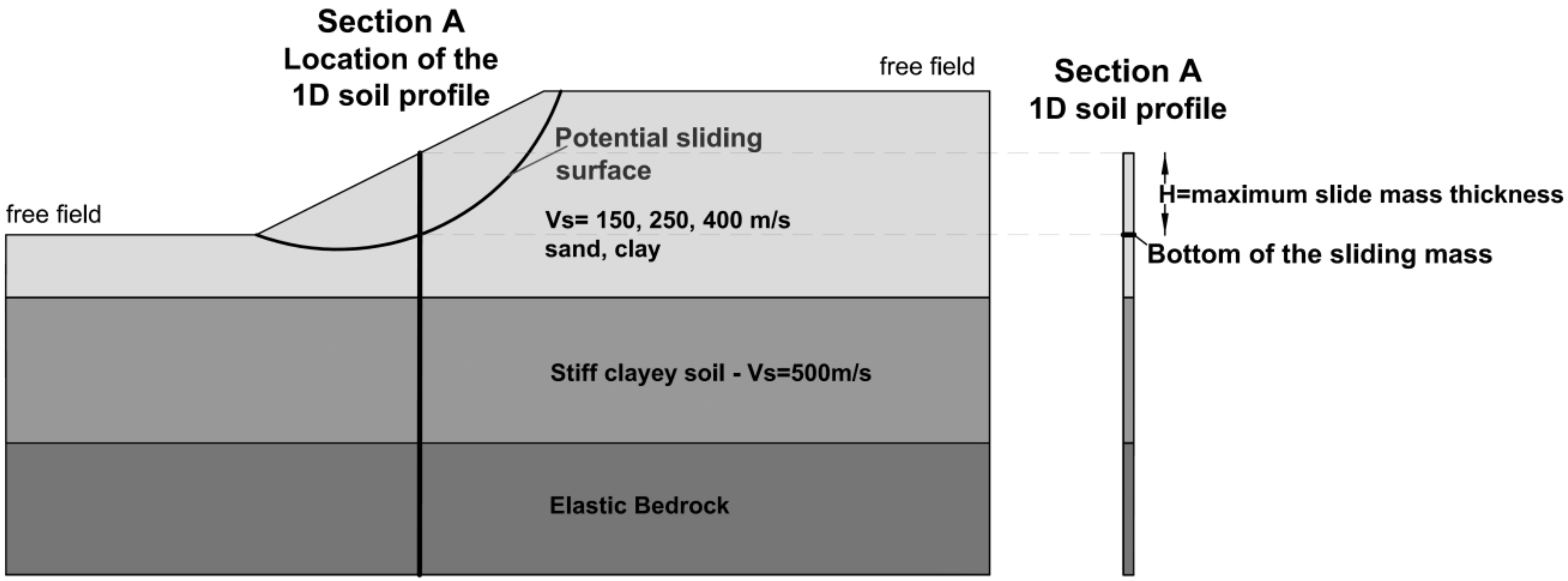
Computed permanent horizontal displacements

Histogram of the computed non-zero (≥0.001m) horizontal displacements



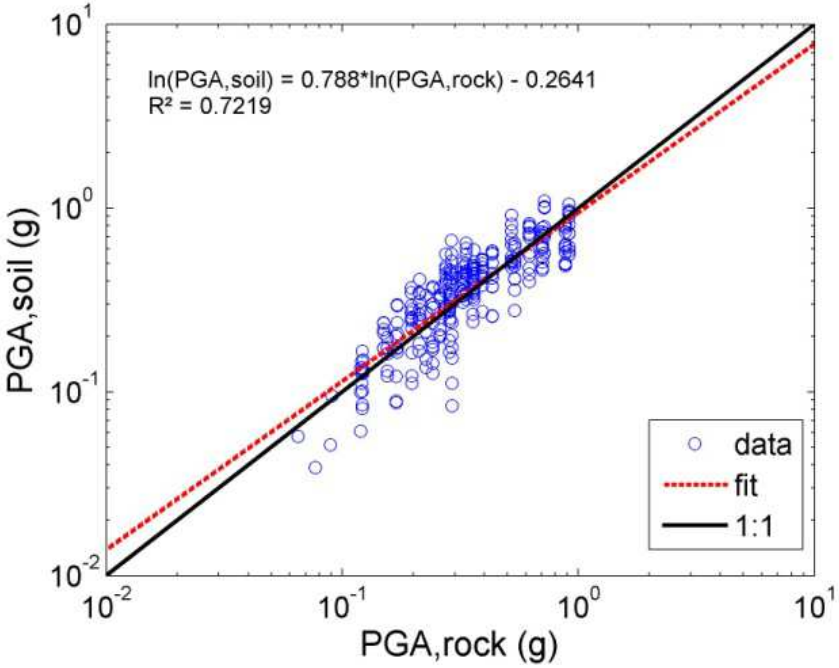
Comparison of the numerical approach with the empirical Newmark-type methods

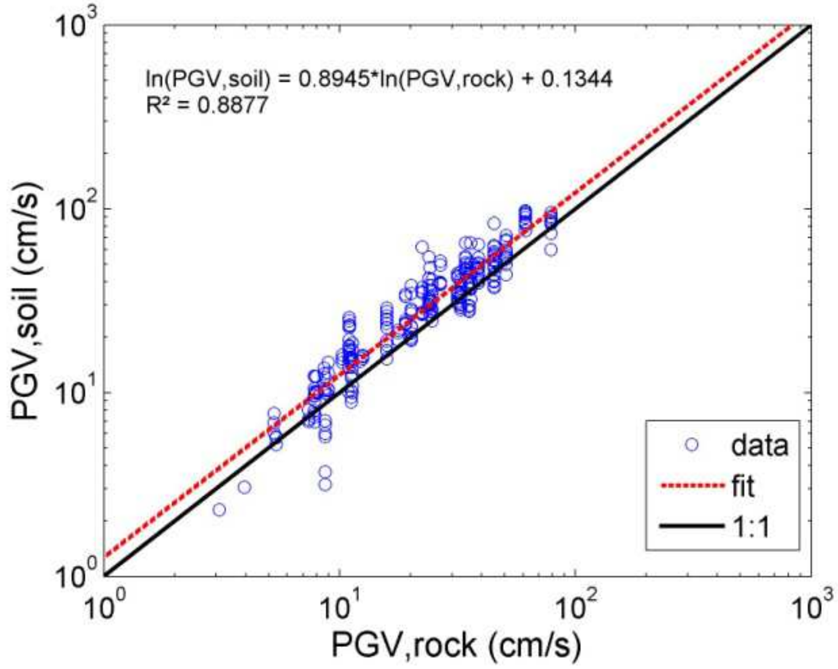
1D nonlinear site response analysis in FLAC to derive the appropriate inputs for the Newmark-type methods at the depth of the sliding surface



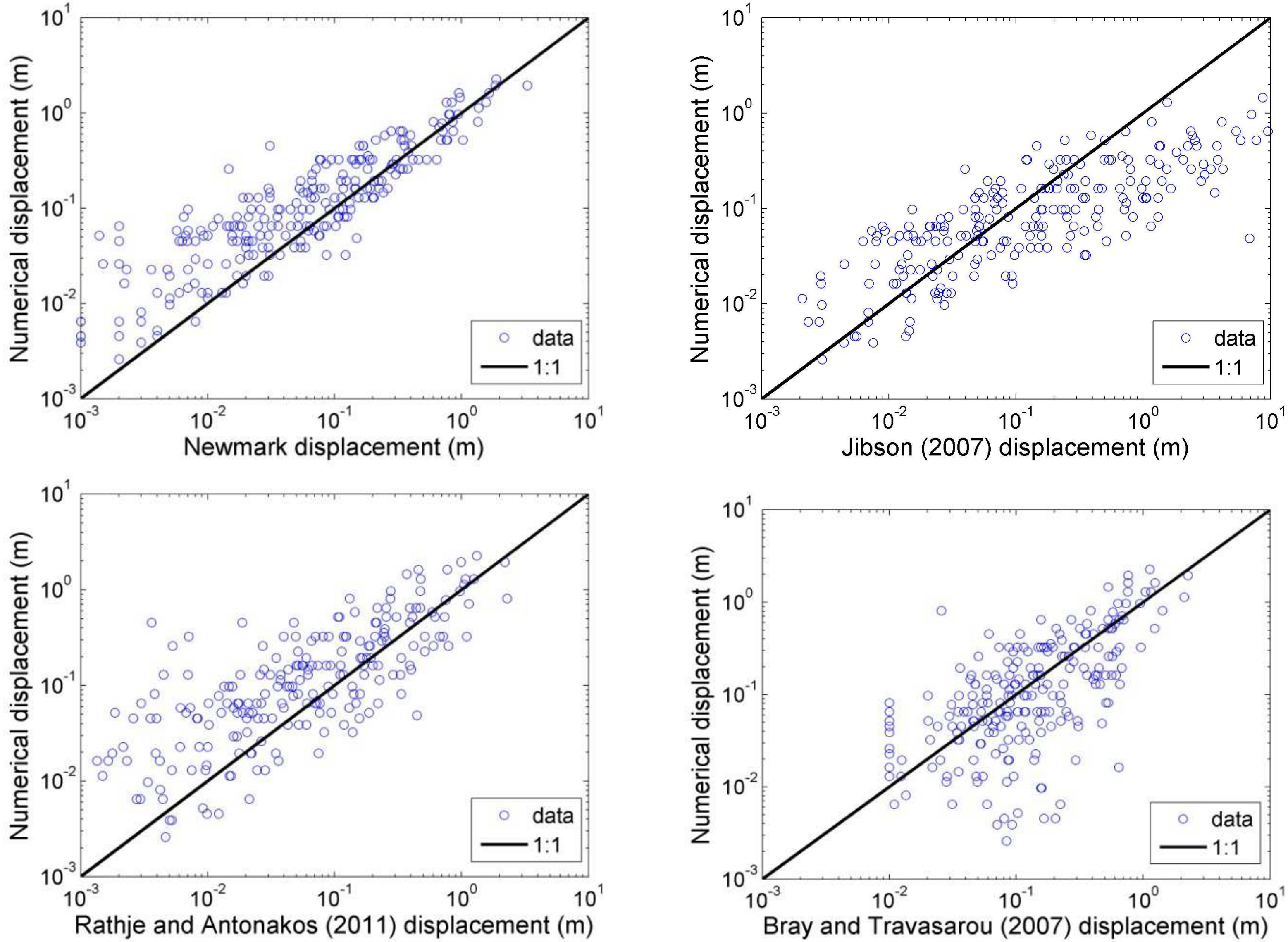
Comparison of the numerical approach with the empirical Newmark-type methods

Variation of PGA and PGV of the input outcropping accelerograms with the corresponding calculated PGA and PGV at the depth of the sliding surface

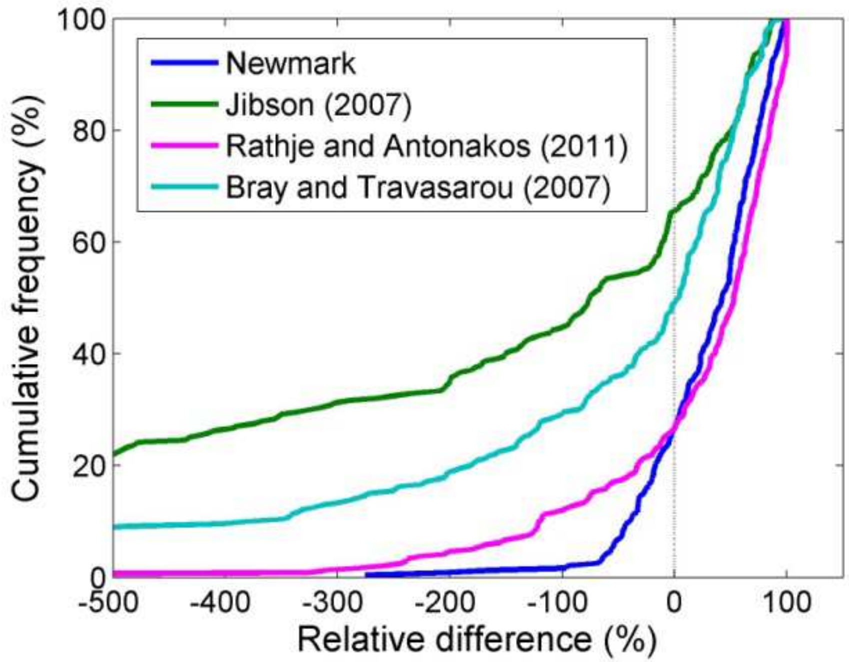




Comparison of the numerical approach with the empirical Newmark-type methods



Comparison of the numerical approach with the empirical Newmark-type methods



Cumulative distribution of the Relative difference (%) *between* ***numerical - empirical slope displacements*** *for each of the empirical sliding block model*

$$\text{Relative difference (\%)} = \frac{D_{\text{numerical}} - D_{\text{empirical}}}{D_{\text{numerical}}} \cdot 100\%$$

- ***For relative difference>0*** → **the empirical methods underpredict the numerical displacements**

Comparison of the numerical approach with the empirical Newmark-type methods

Discussion

- **Numerical displacements are** generally **not inconsistent** with the predicted Newmark-type displacements
- **Newmark method** generally **predicts smaller displacements** and presents the **minimum dispersion** with respect to the numerical approach
- **Jibson (2007)** model **underpredicts small displacements and overpredict large displacements**
- **Rathje & Antonakos (2011)** model is **well compared to the numerical analysis**, except for a group of under-predicted displacements at the small displacement range
- **Bray & Travasarou (2007)** model is generally **in good agreement** with the numerical analysis

New predictive relationships

Definition of main terms

- **Efficiency:** **the conditional uncertainty in response given ground motion intensity**
- **Practicality:** **refers to whether or not there is any direct correlation between an intensity measure (IM) and the demand (seismic slope displacement)**
- **Proficiency:** **a measure of the composite effect of efficiency and practicality**
- **Sufficiency:** **sufficient IMs are those for which consideration of additional ground motion parameters does not reduce the uncertainty in response**

New predictive relationships

Development of regression models using optimal scalar intensity measures

The **optimal scalar IM** is identified through **regression analyses** correlating the **numerical seismic slope displacements (D)** with **various IMs**:

-**Peak ground acceleration (PGA)**

-**Peak ground velocity (PGV)**

-**Arias intensity (I_a)**

-**Mean period (T_m)**

-**Spectral acceleration at a degraded period equal to $1.5T_s$ ($S_a(1.5T_s)$)**

-**k_y/PGA**

New predictive relationships

Development of regression models using optimal scalar intensity measures

IMs were rated based on two different criteria:

•**Proficiency *i.e.* a composite measure of efficiency and practicality** *(Padgett et al. 2007)* → the primary factor in the selection process

•**Sufficiency (*Luco & Cornell 2007*)** → a secondary factor

New predictive relationships

Development of regression models using optimal scalar intensity measures

Linear regression of the logarithms of the IMs and the seismic slope displacement (D) $\ln(D)=b\cdot\ln(IM)+\ln(a)+\varepsilon\cdot\sigma$

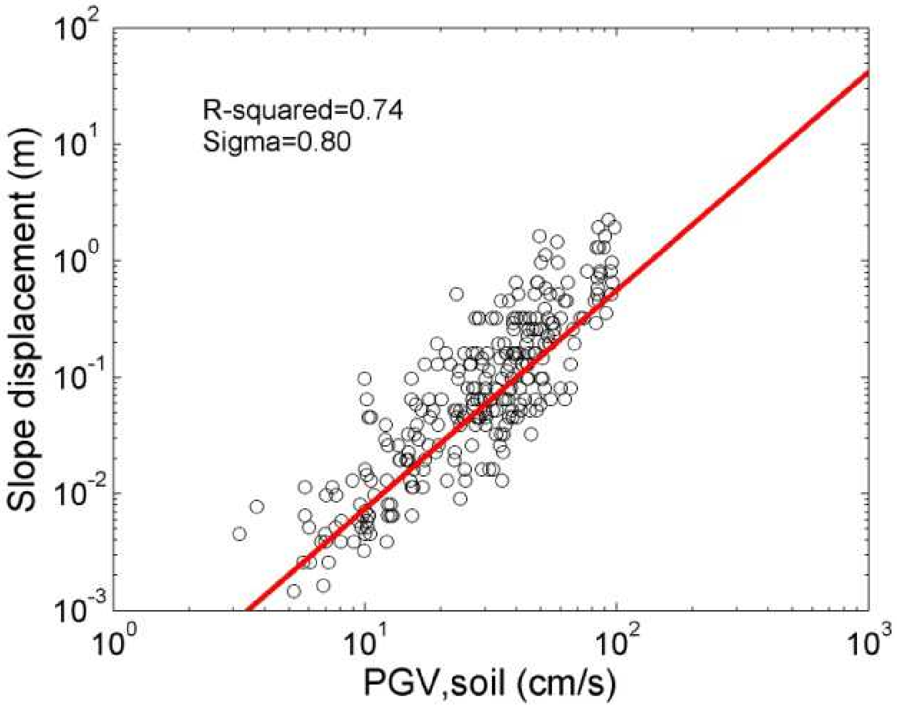
sigma (σ) : the conditional standard deviation of the regression in natural log units (a metric of **efficiency**)
Lower σ values → more efficient IM

b : regression parameter (a metric of the **practicality)**
Lower b values → less practical IM

More proficient IM → a lower modified dispersion ζ= sigma/b

New predictive relationships

Development of regression models using optimal scalar intensity measures



Regression of seismic slope displacement for quantifying the efficiency and practicality of PGV as IM

New predictive relationships

Development of regression models using optimal scalar intensity measures

IM	ln(a)	b	sigma	ζ
PGA (g)	- 0.428	2.127	0.93	**0.44**
PGV (cm/s)	- 8.892	1.873	0.80	**0.43**
T_m (s)	- 1.455	1.717	1.46	0.85
I_a (m/s)	- 2.944	0.993	0.82	0.82
$S_a(1.5T_s)$	- 1.716	1.588	1.21	0.76
k_y/PGA	- 4.770	-2.165	1.01	**0.46**

- **PGV and I_a are the most efficient IMs whereas PGV is the most proficient one followed by PGA and k_y/PGA**
- **I_a is an efficient IM but it is not practical (low b value) and therefore it should not be considered an optimal IM**

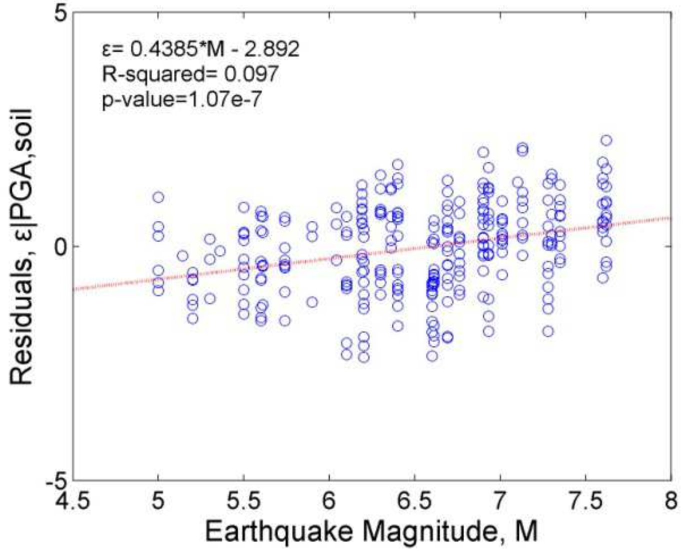
New predictive relationships

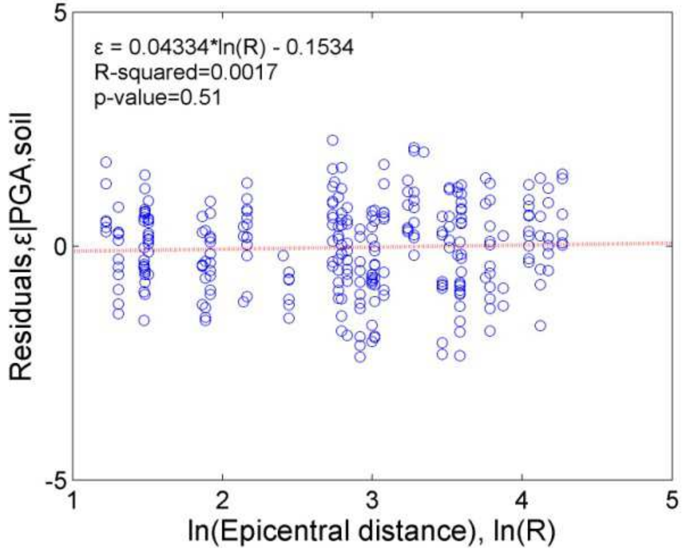
Development of regression models using optimal scalar intensity measures

- **A sufficient IM** is **conditionally statistically independent of ground motion characteristics, such as magnitude (M) and epicentral distance (R)** (*Luco & Cornell 2007*)
- **Sufficiency is evaluated by performing a regression analysis on the residuals, ε|IM, from the numerical seismic slope displacements relative to *M* or *R***
- ***p*-value <0.1 for the linear regression of the residuals on *M* or *R* →insufficient IM**

New predictive relationships

Development of regression models using optimal scalar intensity measures





Sufficiency of PGA as IM by examining the conditional statistical independence from M and lnR

None of the selected IMs satisfies the sufficiency criterion with respect to magnitude and epicentral distance in a rigorous way

New predictive relationships

Development of regression models using optimal scalar intensity measures

k_y is also added to the regression equation where a **linear dependence of the residuals for the considered IMs on** k_y is taken into account:

$$\ln(D)=b\cdot\ln(IM)+\ln(a)+c\cdot k_y+\varepsilon\cdot\sigma$$

IM	ln(a)	b	c	sigma
PGA (g)	0.529	2.127	-6.583	0.80
PGV (cm/s)	-8.028	1.873	-5.964	0.68
k_y/PGA	-5.965	-2.165	7.844	0.82

New predictive relationships

Development of regression models using optimal scalar intensity measures

Magnitude term is also added to the regression equation to **eliminate bias due to magnitude**:

$$\ln(D)=b\cdot\ln(IM)+\ln(a)+c\cdot k_y+d\cdot M+\varepsilon\cdot\sigma$$

IM	ln(a)	b	c	d	sigma
PGA (g)	-2.965	2.127	-6.583	0.535	**0.72**
PGV (cm/s)	-9.891	1.873	-5.964	0.285	**0.65**
k_y/PGA	-10.246	-2.165	7.844	0.654	0.75

New predictive relationships

Development of regression models using optimal vector intensity measures

Vector IMs were selected based on:

- **the proficiency of the scalar IMs,**
- **the correlation coefficient $\rho_{IMi,IMj}$ between them** *(Baker & Cornell 2006)*
- **the overall efficiency of the vector model**

IMs with smaller value of $\rho_{IMi,IMj}$ → smaller standard deviation in the displacement prediction *(Saygili & Rathje 2008)*

	$\rho_{IM1,IM2}$				
IM_1/ IM_2	PGA	T_m	I_a	$S_a(1.5T_s)$	k_y/PGA
PGV	0.75	0.57	0.67	0.59	0.15

New predictive relationships

Development of regression models using optimal vector intensity measures

The functional form used for the regression on a vector of IMs :

$$\ln(D)= \ln(a)+ b\cdot\ln(IM_1)+ e\cdot\ln(IM_2) +\varepsilon\cdot\sigma$$

IM_1 is PGV (cm/s), i.e. the most proficient scalar IM,

IM_2 is the second intensity measure

IM_1	IM_2	ln(a)	b	e	sigma
PGV	k_y/PGA	-9.524	1.873	-0.634	**0.70**
PGV	T_m (s)	-9.250	1.873	-0.444	0.79
PGV	I_a (m/s)	-8.940	1.873	0.072	**0.80**
PGV	PGA (g)	-8.897	1.873	0.025	0.80
PGV	$S_a(1.5T_s)$ (g)	-8.912	1.873	0.018	0.80
PGV	k_y/PGA	-9.524	1.873	-0.634	**0.70**

PGV- I_a and PGV- k_y/PGA the most efficient vector IMs

New predictive relationships

Development of regression models using optimal vector intensity measures

- The **sufficiency criterion** is addressed by considering the M and lnR dependence of the residuals for each pair of IMs.
- the mean residuals of all vectors do not vary with lnR (p-value≥0.10).
- only **PGV-k_y/PGA** and **PGV-I_a** pairs are **statistically independent from M** (p-value≥0.10) →**only these IMs cover the sufficiency criterion**
- **PGV- k_y/PGA** pair has a **lower correlation coefficient & PGV and k_y/PGA the most proficient scalar IMs** →**PGV- k_y/PGA pair the most appropriate vector IM to correlate to seismic slope displacements**

New predictive relationships

Development of regression models using optimal vector intensity measures

k_y term is also incorporated in the regression:

$$\ln(D) = \ln(a) + b \cdot \ln(IM_1) + e \cdot \ln(IM_2) + c \cdot k_y + \varepsilon \cdot \sigma$$

IM_1 (cm/s)	IM_2	ln(a)	b	c	e	sigma
PGV	k_y/PGA	-8.36	1.87	-5.96	-0.35	**0.64**
PGV	T_m (s)	-8.31	1.87	-5.96	-0.38	0.66
PGV	I_a (m/s)	-8.06	1.87	-5.96	0.20	**0.61**
PGV	PGA (g)	-7.67	1.87	-5.96	0.33	0.64
PGV	$S_a(1.5T_s)$ (g)	-7.91	1.87	-5.96	0.19	0.66
PGV	k_y/PGA	-8.36	1.87	-5.96	-0.35	**0.64**

New predictive relationships using numerical analysis results

Suggested scalar and vector predictive models

Scalar models

$$\ln(D) = -9.891 + 1.873\cdot\mathbf{\ln(PGV)} - 5.964\cdot\mathbf{k_y} + 0.285\cdot\mathbf{M} \pm \varepsilon\cdot 0.65$$

$$\ln(D) = -2.965 + 2.127\cdot\mathbf{\ln(PGA)} - 6.583\cdot\mathbf{k_y} + 0.535\cdot\mathbf{M} \pm \varepsilon\cdot 0.72$$

$$\ln(D) = -10.246 - 2.165\cdot\mathbf{\ln(k_y/PGA)} + 7.844\cdot\mathbf{k_y} + 0.654\cdot\mathbf{M} \pm \varepsilon\cdot 0.75$$

Vector models

$$\ln(D) = -8.076 + 1.873\cdot\mathbf{\ln(PGV)} + 0.200\cdot\mathbf{\ln(I_a)} - 5.964\cdot\mathbf{k_y} \pm \varepsilon\cdot 0.61$$

$$\ln(D) = -8.360 + 1.873\cdot\mathbf{\ln(PGV)} - 0.347\cdot\mathbf{\ln(k_y/PGA)} - 5.964\cdot\mathbf{k_y} \pm \varepsilon\cdot 0.64$$

where D is in m, PGA in g, PGV in cm/s and I_a in m/s

The free field ground surface intensity parameters *(i.e. PGA, PGV, I_a) could be used in the equations without any modification with depth*

Otherwise, one could estimate the IMs for soil conditions (e.g. at the depth of the sliding surface) given the corresponding IMs at the rock outcrop using the proposed simplified expressions derived from the dynamic analysis or alternatively using the site amplification factors proposed in the previous presentation *(Pitilakis and Riga 2016)*

New predictive relationships using numerical analysis results

Suggested scalar and vector predictive models

Scalar models:

$\ln(D) = -9.891 + 1.873 \cdot \mathbf{\ln(PGV)} - 5.964 \cdot \mathbf{k_y} + 0.285 \cdot \mathbf{M} \pm \varepsilon \cdot 0.65$

$\ln(D) = -2.965 + 2.127 \cdot \mathbf{\ln(PGA)} - 6.583 \cdot \mathbf{k_y} + 0.535 \cdot \mathbf{M} \pm \varepsilon \cdot 0.72$

$\ln(D) = -10.246 - 2.165 \cdot \mathbf{\ln(k_y/PGA)} + 7.844 \cdot \mathbf{k_y} + 0.654 \cdot \mathbf{M} \pm \varepsilon \cdot 0.75$

Vector models:

$\ln(D) = -8.076 + 1.873 \cdot \mathbf{\ln(PGV)} + 0.200 \cdot \mathbf{\ln(I_a)} - 5.964 \cdot \mathbf{k_y} \pm \varepsilon \cdot 0.61$

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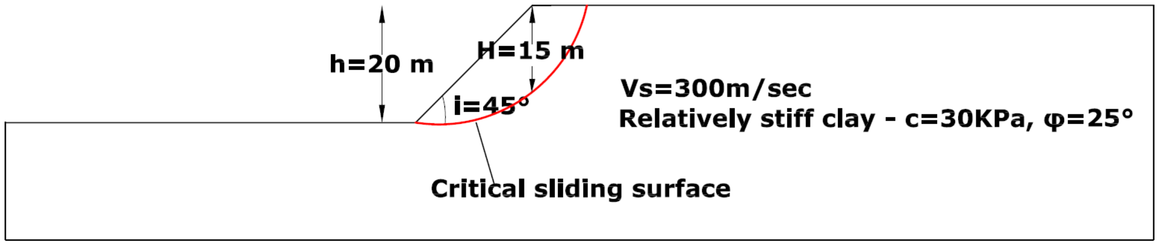
where D is in m, PGA in g, PGV in cm/s and I_a in m/s

The free field ground surface intensity parameters *(i.e. PGA, PGV, I_a) could be used in the equations without any modification with depth*

New predictive relationships : Examples

Example application I



- Natural step-like slope
- Yield coefficient **k_y =0.1**
- Elastic fundamental period of the slide mass **T_s =4*H/Vs=0.2s**
- **Scenario earthquake:** real ground motion (SHARE database) recorded on soil class C (EC8) with M_w=6.93 and R=30 km

Estimated ground motion IMs of the given earthquake event

PGA (g)	PGV(cm/s)	T_m (s)	I_a (m/s)	Sa(1.5T_s) (g)
0.363	32.87	0.526	1.197	0.715

New predictive relationships

Example application I

		Seismic slope displacement (m)		
		Median (or mean)	Median (or mean) + 1σ	Median (or mean)- 1σ
Scalar models	PGV- M	0.140	0.267	0.073
	PGA-M	0.126	0.259	0.061
	k_y/PGA-M	0.118	0.249	0.056
Vector models	PGV- I_a	0.123	0.226	0.067
	PGV-k_y/PGA	0.140	0.241	0.074
Newmark		0.088	-	-
Jibson 2007		0.355	0.657	0.192
Rathje & Antonakos 2011		0.148	0.240	0.091
Bray& Travasarou 2007		0.259	0.499	0.134

New predictive relationships

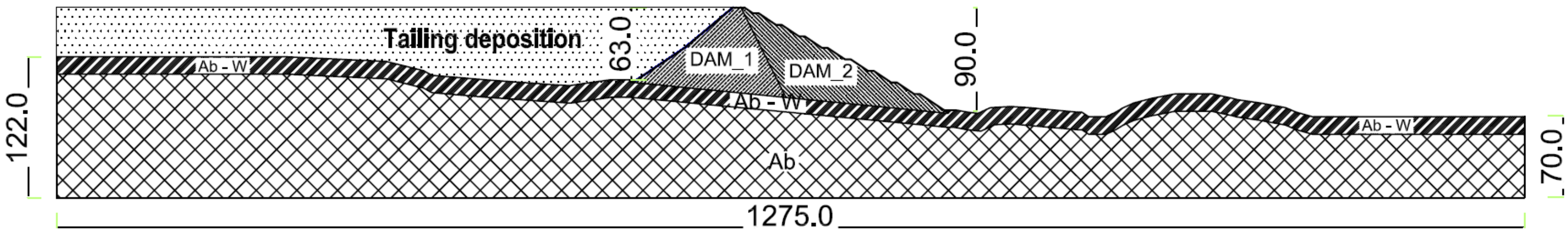
Example application I

- Fotopoulou and Pitilakis (2015) models predict consistent displacement for the considered earthquake scenario and slope properties →median values vary from **0.118 to 0.140m**
- For the scalar models, the estimated median+1σ and median-1σ displacements are about **two times** and **half** the median value respectively
- For the vector models, the estimated range of the median±1σ displacements is even more converged
- **Newmark analytical method** presents **25-37% smaller average displacements**
- **Jibson (2007), Rathje & Antonakos (2011)** and **Bray & Travasarou (2007) models over predict displacements by 150-200%**, **6-25%** and **85-120% respectively**

New predictive relationships

Example application II

- Tailing dam in Chalkidiki (northen Greece)
- Yield coefficient **k_y =0.23**
- Elastic fundamental period of the slide mass **T_s =0.16s**
- **Scenario earthquake:** real ground motion (SHARE database) recorded on soil class C (EC8) with M_w=6.93 and R=30 km



New predictive relationships

Example application II

		Seismic slope displacement (m)		
		Median (or mean)	Median (or mean) + 1σ	Median (or mean)- 1σ
Scalar models	PGV- M	0.064	0.123	0.034
	PGA-M	0.054	0.110	0.026
	k_y/PGA-M	0.054	0.114	0.025
Vector models	PGV- I_a	0.057	0.104	0.031
	PGV-k_y/PGA	0.048	0.091	0.025
Newmark		0.005	-	-
Jibson 2007		0.014	0.027	0.008
Rathje & Antonakos 2011		0.009	0.017	0.005
Bray& Travasarou 2007		0.052	0.102	0.025

New predictive relationships

Example application II

- Fotopoulou and Pitilakis (2015) models predict consistent displacement for the considered earthquake scenario and slope properties →median values vary from **0.048 to 0.064m**
- For the scalar models, the estimated median+1σ and median-1σ displacements are about **two times** and **half** the median value respectively
- For the vector models, the estimated range of the median±1σ displacements is even more converged
- **Bray & Travasarou (2007) method** predicts **displacements that are in good agreement with Fotopoulou and Pitilakis (2015) models**
- **Jibson (2007), Newmark and Rathje & Antonakos (2011) models underpredict displacements by 71-78%**, **89-92%** and **82-86% respectively**

Conclusions

- **New predictive analytical models** for assessing the **co-seismic slope displacements** based on **numerical analysis** and **advanced statistics**
- The numerically estimated seismic slope displacements were compared with existing **empirical Newmark-type models**
- **Optimal scalar and vector IMs** based on **proficiency** and **sufficiency** criteria
- The **deterministic examples** have shown that all proposed models predict **consistent seismic slope displacements** for the considered earthquake scenario and slope/dam properties
- The comparison with the empirical approaches illustrated **the large variability in the displacement prediction highlighting the need for a probabilistic approach in the seismic displacement prediction**

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