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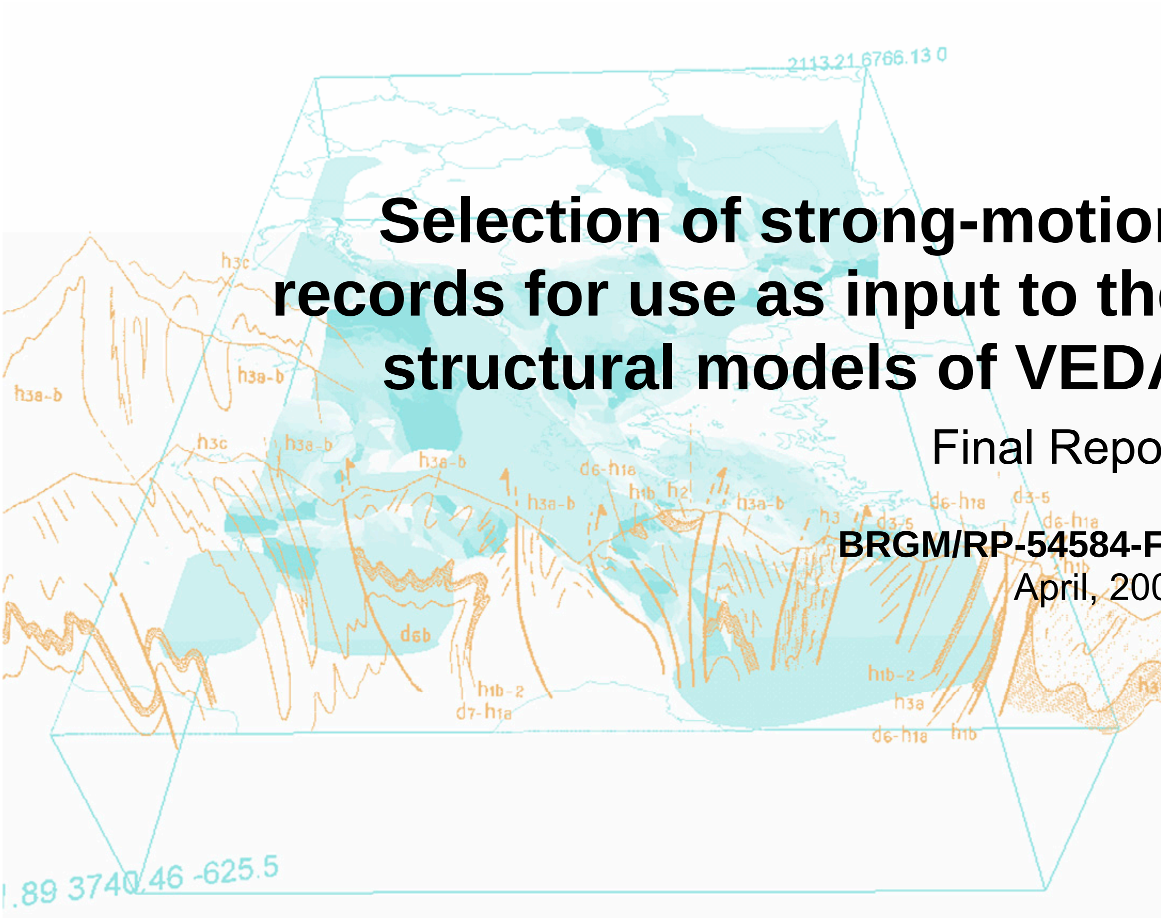

Selection of strong-motion records for use as input to the structural models of VEDA

Final Report

BRGM/RP-54584-FR

April, 2006

Geoscience for a sustainable Earth

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Selection of strong-motion records for use as input to the structural models of VEDA

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Study carried out as part of
Research activities - BRGM 2006 PDR06ARN11

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Synopsis

The ANR-funded project 'Seismic Vulnerability of structures: A damage mechanics approach' (VEDA) has a goal to propose improved fragility curves for the estimation of damage induced by earthquake shaking. These curves will be produced by combining numerical models for a series of typical French building typologies developed during the project with strong-motion records from previous earthquakes. It is planned to investigate the utility of using different strong-motion parameters to characterise the seismic intensity and not simply a parameter characterising the amplitude of the motions as is commonly used today, e.g. peak ground acceleration. For example, the addition of parameters characterising the duration of earthquake ground motions could lead to an improved prediction of earthquake damage.

This report and accompanying CD ROM are deliverables of Workpackage (WP) 2.1 (Characterisation of seismic hazard) of VEDA. This report presents the methodology adopted to select an optimal set of strong-motion records for use as input to the structural models and also lists the strong-motion records chosen. The associated CD ROM contains ASCII files of the selected strong-motion records plus a Microsoft Excel spreadsheet that lists the associated event, path and site parameters of the records and various computed strong-motion parameters.

The produced CD ROM will be used as input within WP2.2 (Use of damage models) and WP2.3 (Proposition of fragility curves) later on in the project.

This report does not explicitly consider the selection of strong-motion records for the French Antilles, where both subduction and shallow crustal earthquakes occur, but focuses on choosing records that are appropriate for metropolitan France, where the seismicity is only characterised by shallow crustal earthquakes.

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1. Introduction

1.1. SEISMIC FRAGILITY CURVES

Seismic fragility curves express the damage expected to a given type of building as a function of the intensity[1] of the earthquake ground motion. These curves are usually in the form of one curve per damage level (e.g. no damage, light damage or serve damage) that give the percentage of buildings expected to obtain that level of damage for a given ground motion. By combining these curves with an estimation of the ground motion at each structure, the expected level of damage due to an earthquake can be predicted within an earthquake damage assessment (see Illustration 1). It is currently common to express the ground motion in terms of a single amplitude parameter, for example peak ground acceleration or spectral displacement for a given period and damping level. However, earthquake ground motion is a highly complex phenomenon (for example see Illustration 2) and therefore the characterisation of earthquake ground motion by a single number leads to some of the inaccuracy within earthquake risk assessment.

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[1] Note that this should not be confused with macroseismic intensity, which expresses the level of damage that occurred during an earthquake. For basic earthquake risk assessments It can also be used to characterise the seismic hazard (e.g. Level I of RISK-UE) but this approach is not discussed here.

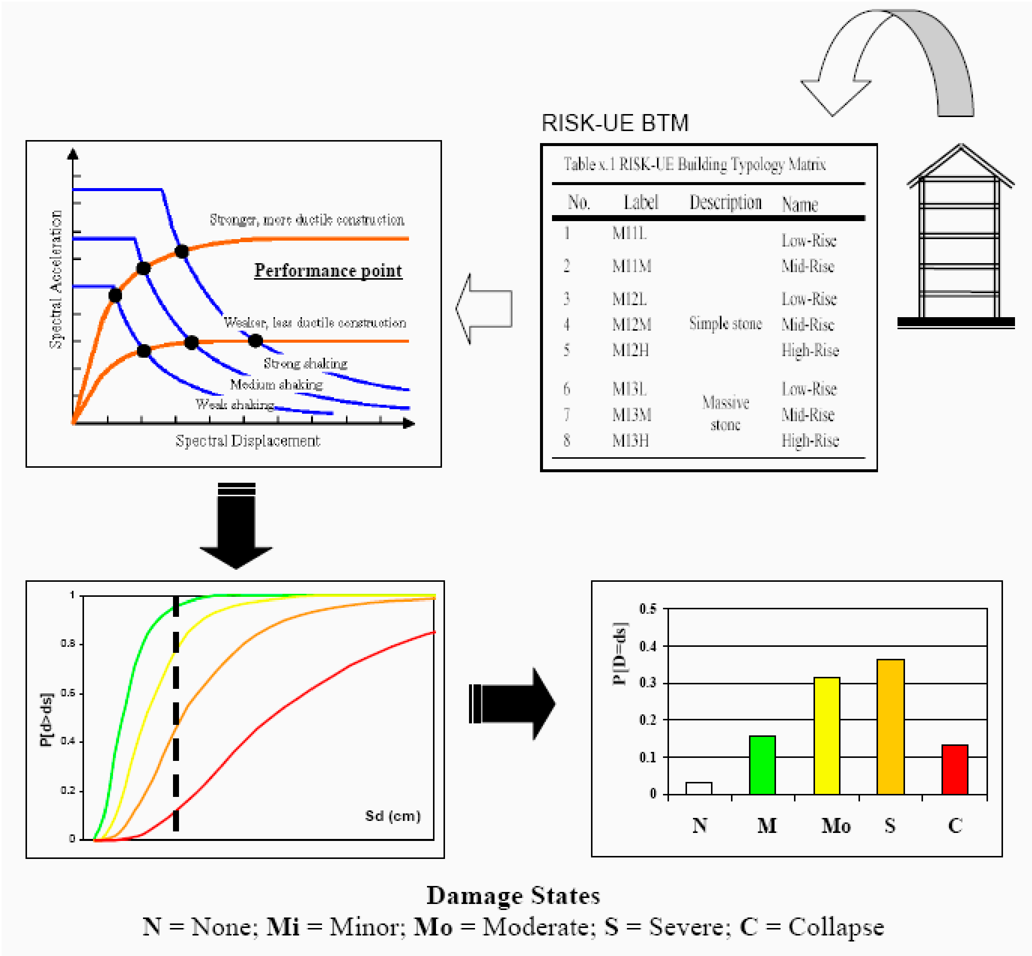

Illustration 1 : Method of evaluation of earthquake damage estimation within RISK-UE (Milutinovic & Terndafiloski, 2003).

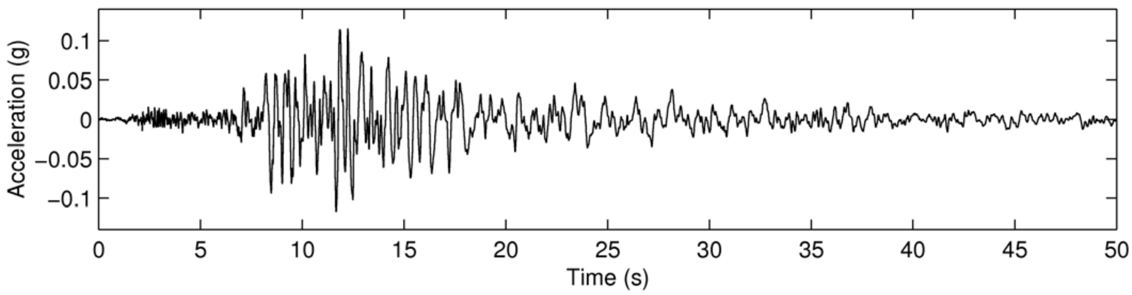

Illustration 2 : Horizontal ground accelerations recorded at Pointe-à-Pitre (Ecole Lauricisque) during the Les Saintes (Guadeloupe) earthquake (21st November 2004).

1.2. GOAL OF VEDA

The goal of the ANR-funded project ‘Seismic Vulnerability of structures: A damage mechanics approach’ (VEDA) is to propose seismic fragility curves for a set of typical French building typology (framed structures and reinforced concrete structures). These fragility curves will be estimated using a damage mechanics approach that computes the damage within a numerical model of the structure following the input of natural strong-motion records to simulate the effect of an earthquake. A novelty of VEDA is that it is proposed to develop fragility curves using more than one parameter to characterise the intensity of the earthquake ground motions. It is hoped this inclusion of more characteristics of the earthquake ground motion, such as the duration of the shaking, will lead to a reduction in the inaccuracies within the transformation from hazard parameters to estimated damage.

1.3. PURPOSE OF THIS REPORT

The purpose of this report is two fold. Firstly it documents the methodology used to select strong-motion records that will be used as input to the structural models developed within VEDA (chapter 2). Secondly it presents the strong-motion records selected and the contents of the accompanying CD ROM containing these strong-motion records and also a Microsoft Excel spreadsheet containing the computed strong-motion parameters for all the records selected (chapter 3). Appendix 1 lists the strong-motion records selected and their associated parameters (earthquake magnitude, source-to-site distance etc.).

Since it is not currently known which characteristics of strong ground motions are most important for predicting the damage sustained to the structures investigated within VEDA, it is proposed to follow a two stage approach. In the first stage a small set of strong-motion records with widely different characteristics are used as input to the structural models. From the results of these simulations the strong-motion parameters that are most useful for predicting the damage to the structures can be found. The purpose of this report is the selection of this small set of records. In the second stage (to be conducted in 2007 and 2008) a set of records with varying values of the strong-motion parameters that were found to be most important for construction of the fragility curves will be chosen. These records will then be used as input to structural simulations and from the results fragility curves will be constructed using the selected parameters as measures of the seismic intensity.

2. Selection of strong-motion records

2.1. STRONG-MOTION RECORDS AS INPUT TO STRUCTURAL MODELS

At present there are many sources of earthquake strong-motion records on the Internet, e.g. ISESD (http://www.isesd.cv.ic.ac.uk), COSMOS (http://db.cosmos-eq.org/scripts/default.plx) or the PEER NGA database (http://peer.berkeley.edu/nga/index.html), or on CD ROMs (e.g. Seekins et al., 1992; Ambraseys et al., 2004) that could be used to provide many thousands of records as input to the structural models of VEDA. However, since the structural models that it is planned to develop within VEDA are complex and consequently take time to run it is important that a small selection of strong-motion records are chosen in order to cut down the number of runs required but to obtain well-constrained seismic fragility curves.

In order to reduce the complexity of the modelling it is planned to subject the numerical structural model to one-dimensional horizontal excitation. Therefore in this report only horizontal components of ground motions are considered and the two horizontal components from the same triaxial strong-motion record are considered independently.

Accelerograms selected in this report are to be used as input to complex numerical models of structures whose structural parameters are to be varied. Since the run times of these numerical models are long (many hours) it is important that the number of input strong-motion records is kept to a minimum but at the same time allowing the behaviour of the structures to be investigated and also the uncertainty of this behaviour understood.

In order that an efficient set of input accelerograms is selected some ideas from the theory of Design of Experiments (DOE) (e.g. http://www.itl.nist.gov/div898/handbook/pri/section1/pri1.htm) are employed. Well design experiments maximize the amount of *information* that can be obtained for a given amount of experimental effort.

Since one purpose of VEDA is to decide which characteristics of strong ground motions are important for different types of structures and consequently to derive improved fragility curves to predict the damage due to earthquakes, the experimental design required has a *screening objective*. The primary purpose of these experiments is to select or *screen out* the few important main effects from the many less important ones. These designs are also termed *main effects* designs.

In the terminology of *black box process models* of DOE, the structural model is the *process* and the estimated damage parameters from these models are the *outputs* (*responses)*. The *controlled inputs* (*factors*) are split into the parameters defining the structural model (strength of concrete etc.) and the input ground motions. At this stage, there are no *uncontrolled inputs (co-factors)* since everything can be set by the experimenter. Since there is an infinite variety of possible earthquake ground motions it is useful to characterise them using a number of scalar strong-motion parameters that approximately measure different properties of the motions (amplitude, frequency content, duration, energy etc.). Hence the set of strong-motion parameters becomes the controlled inputs to the process. The benefit of this approach is that it is then easier to understand the results of the structural modelling with respect to properties of the input accelerograms. However, since these strong-motion parameters do not perfectly characterise the ground motions (no small set of scalars can hope to fully characterise the true complexity of ground motions) the use of strong-motion parameters introduces uncontrolled factors (co-factors) due to the complexity of the motions not measured by the strong-motion parameters chosen.

The strong-motion parameters chosen define the *main effects* in the model.

Since we do not know *a priori* which strong-motion parameters are the most appropriate to construct fragility curves for each type of structure studied a screening study is required. It is hoped that the result of this screening process will be a preliminary list of which strong-motion parameters are useful to investigate as possible measures of the seismic intensity for the construction of fragility curves.

2.2. STRONG-MOTION PARAMETERS

This section lists all the strong-motion parameters considered for this report and given on the associated CD ROM. Kramer (1996, pp. 65-84) gives a good overview of many of these different strong-motion parameters. See Hancock (2006) for a more comprehensive survey of strong-motion parameters and their limitations.

Since they will obviously be strongly correlated to their constitutive parts composite strong-motion parameters that combine two or more simpler strong-motion parameters, such as the damage factor J_I proposed by Fajfar et al. (1989), are not considered here.

2.2.1. Peak ground acceleration, PGA

Defined as the absolute maximum acceleration within the strong-motion record.

2.2.2. Peak ground velocity, PGV

Defined as the absolute maximum velocity within the strong-motion record.

2.2.3. Peak ground displacement, PGD

Defined as the absolute maximum displacement within the strong-motion record.

2.2.4. Elastic response spectral ordinates

A very common tool for the assessment of structural behaviour during earthquakes is the elastic response spectrum based on the analysis of single-degree-of-freedom (SDOF) elastic models of natural period, T, and viscous damping, ξ. Although the response of such a system changes with time, which may be important for some applications, often only the maximum response that a system undergoes is required for design purposes. Consider a SDOF elastic model of mass m, with displacement $u(t)$, velocity $u_t(t)$ and acceleration $u_{tt}(t)$ subjected to a ground acceleration of $U_{tt}(t)$. A number of system response parameters can be defined, which are given below. A plot of these response parameters as a function of T and ξ is called a response spectrum. It provides a convenient means of summarizing the peak response of all possible linear SDOF systems to a particular component of ground motion.

In addition, inelastic response spectra can be defined based on force-displacement functions that are not linear but, for example, have a bilinear form that models either strain-softening or strain-hardening of the structure. These more complex models have not been considered here since it is often possible to estimate inelastic spectral ordinates from elastic spectral ordinates by approximate conversion formulae (e.g. Miranda & Bertero, 1994). For this study inelastic constant strength and constant ductility spectra are calculated using an elastoplastic force-displacement relation.

Chopra (1995) provides a good introduction to both elastic and inelastic response spectra.

Maximum absolute response acceleration, S_a

Defined as: $S_a=\max_t|u_{tt}+U_{tt}|$. mS_a gives the maximum force acting that must be resisted by the entire system.

Maximum relative response velocity, S_v

Defined as: $S_v= \max_t|u_t|$.

Maximum relative response displacement, S_d

Defined as: $S_d= \max_t|u|$. This response parameter has been chosen to characterise motions within VEDA because of its use to define many recent fragility curves (e.g. the fragility curves of Level 2 of the RISK-UE methodology). In fact, for most periods and damping levels of engineering interest the different spectral response parameters (S_a, S_v and S_d) are highly correlated so only one is needed in the construction of fragility curves.

Maximum absolute pseudo-acceleration, S'_a

From the maximum relative response displacement the maximum absolute pseudo-acceleration is defined as: $S'_a=(2\pi/T)^2S_d$. mS'_a gives the force that must be resisted by the spring (Chopra, 1995) and not the complete system. For small coefficients of critical damping and relative short periods S_a and S'_a are almost identical (Chopra, 1995).

Maximum absolute pseudo-velocity, S'_V

Similar to the pseudo-acceleration defined above, the maximum absolute pseudo-velocity is defined as: $S'_V=(2\pi/T)\ S_d$. $mS'_V{}^2/2$ gives the peak value of the strain energy stored in the system during the earthquake (Chopra, 1995, p. 200).

2.2.5. Maximum absolute input energy, *I*

Similarly to the elastic response spectrum, elastic energy spectra can also be defined based on the elastic response of a SDOF system. The maximum absolute input energy, I, is defined as (Chapman, 1999):

$$I = \max_t \int_0^t [u_{tt}(t) + U_{tt}(t)] U_t(t) dt$$

2.2.6. Arias intensity, AI

Defined as:

$$AI = \frac{\pi}{2g} \int_0^T U_{tt}{}^2 dt$$

where T is the length of the acceleration time-history and g is acceleration due to gravity (here assumed to be $9.80665 ms^{-2}$) (Arias, 1970).

AI provides a measure of the amount of energy within the acceleration time-history.

2.2.7. A_{95}

Based on the Arias intensity, Sarma & Yang (1987) define a strong-motion parameter called A_{95} defined as that level of acceleration which contains up to 95% of the Arias intensity. It is proposed since PGA is often associated with high frequency motions that do not contain significant energy and also PGA is difficult to predict.

2.2.8. Slope of the Husid plot, $SLOPE_{75}$ and $SLOPE_{95}$

One characteristic of earthquake ground motion that is difficult to characterise in terms of a strong-motion parameter is the shape of the accelerogram, in terms of how rapidly the strong shaking builds up and dies away at the end. This is connected to the rate of energy input into a structure and hence could be important as a indicator of the ability of a particular motion to damage a structure. A set of parameters that roughly characterise this rate are the slopes of the Arias intensity between different percentages of the total Arias intensity, usually 5 and 75% ($SLOPE_{75}$) or 5 and 95% ($SLOPE_{95}$) (Bommer et al., 2004).

2.2.9. Normalised energy density, NED

Defined as:

$$NED = \int_0^T U_t(t)^2 dt$$

where $U_t(t)$ is ground velocity at time t and T is the length of the velocity time-history (Sarma, 1971). To obtain the true energy density the normalised energy density must be multiplied by $S\rho/4$, where S is the wave speed in the material carrying the wave and ρ is the mass density of the material (Sarma, 1971). However, since the site where the structures of VEDA are situated is not known in this report only the normalised energy density is considered here.

2.2.10. Housner spectral intensity, SI

Defined as:

$$SI = \int_{T_1}^{T_2} S'_v(\xi, T) dT$$

where T_1 and T_2 are period limits (taken here, as usual, to be 0.1 and 2.5s) (Housner, 1959).

2.2.11. Acceleration spectral intensity, ASI

Defined as:

$$ASI = \int_{T_1}^{T_2} S_a(\xi, T) dT$$

where T_1 and T_2 are period limits (taken here, as usual, to be 0.1 and 0.5s) (Von Thun et al., 1988). From ASI, the effective peak ground acceleration (EPGA) is calculated using $EPGA=ASI/[2.5(T_2-T_1)]$ (ATC, 1978).

2.2.12. Durations

Durations, both absolute and relative (bracketed, uniform and significant) have been calculated. The definitions in absolute and relative terms are given in the next section. The sign of the ground acceleration is not important when defining the bracketed or uniform durations – the exceedence of a threshold is defined in absolute terms. Bommer & Martinez-Pereira (1999) provide a comprehensive review of strong-motion parameters of duration.

Bracketed (absolute), τ_{BA}

Length of interval between the first and last time the ground acceleration exceeds a threshold value (usually 0.05g) (Bolt, 1973).

Uniform (absolute), τ_{UA}

Total length of time for which ground acceleration exceeds a threshold value. It follows from the definitions that the absolute bracketed duration is greater than or equal to the absolute uniform duration for a given acceleration and any given threshold.

Significant (absolute), τ_{SA}

Length of interval between when Arias intensity first exceeds a threshold value (usually 0.01ms^{-1}) and the time when Arias intensity first exceeds total Arias intensity of record minus some threshold value (usually 0.125ms^{-1}). Bommer & Martinez-Pereira (1999) call this ‘effective’ duration.

Bracketed (relative), τ_{BR}

Length of interval between the first and last time the ground acceleration exceeds a threshold value defined as a percentage of peak ground acceleration.

Uniform (relative), τ_{UR}

Total length of time for which ground acceleration exceeds a threshold value defined as a percentage of peak ground acceleration. As for the absolute definition, it follows that the relative bracketed duration is greater than or equal to the relative uniform duration for a given acceleration and any given threshold.

Significant (relative), τ_{SR}

Length of interval between when Arias intensity first exceeds a threshold value defined as percentage of total (usually 5%) and time when Arias intensity first exceeds a different threshold value defined as percentage of total (usually 95%) (Trifunac & Brady, 1975).

2.2.13. Root-mean-square acceleration, a_{rms}

Defined as:

$$a_{rms} = \sqrt{\frac{1}{T_e - T_b} \int_{T_b}^{T_e} a(t)^2 \, dt}$$

where *a(t)* is ground acceleration at time *t*, T_b is the time at the beginning of the interval of interest and T_e is the time at the end of the interval of interest. In this report T_b and T_e are taken as 0 and the end of the record, respectively.

2.2.14. Mean period, T_m

In order to characterise the frequency content of strong ground motions, Rathje et al. (2004) investigate a number of parameters based on the frequency content of Fourier amplitude spectra and elastic response spectra. Rathje et al. (2004) conclude that T_m defined as:

$$T_m = \frac{\sum_i C_i^2 (1/f_i)}{\sum_i C_i^2} \text{ for } 0.25\text{Hz} \leq f_i \leq 20\text{Hz, with } \Delta f \leq 0.05\text{Hz}$$

where C_i are the Fourier amplitude coefficients, f_i are the discrete fast Fourier transform (FFT) frequencies between 0.25 and 20Hz, and Δf is the frequency interval used in the FFT computation, is the most appropriate measure of the frequency content of the four parameters studied.

2.2.15. Predominant spectral period, T_p

Defined as the period of the maximum spectral acceleration (Rathje et al., 2004). Rathje et al. (2004) do not recommend that this parameter is used since it is unstable and cannot be predicted accurately. Hence it is not considered here.

2.2.16. Smoothed spectral predominant period, T_0

Defined as (Rathje et al., 2004):

$$T_0 = \frac{\sum_i T_i \ln\left(\frac{S_a(T_i)}{PGA}\right)}{\sum_i \ln\left(\frac{S_a(T_i)}{PGA}\right)} \text{ for } T_i \text{ with } S_a/PGA \geq 1.2,\ \Delta\log T_i \leq 0.02$$

where T_i are discrete periods in the acceleration response spectrum equally spaced on a logarithmic axis.

2.2.17. Average spectral period, T_{avg}

Defined as (Rathje et al., 2004):

$$T_{avg} = \frac{\sum_i T_i \left(\frac{S_a(T_i)}{PGA}\right)^2}{\sum_i \left(\frac{S_a(T_i)}{PGA}\right)^2} \text{ for } 0.05 \leq T_i \leq 4\text{s},\ \Delta T_i \leq 0.05\text{s}$$

where T_i are discrete periods in the acceleration response spectrum equally spaced on an arithmetic axis.

2.2.18. Number of cycles, N_{cy}, and cyclic damage parameter

Earthquake ground motion features many cycles of motion that can have a damaging effect on structures. However, since the cycles are high inhomogeneous in terms of frequency, amplitude and form there have been many proposals to count the number of effective cycles in a given strong-motion record. Hancock & Bommer (2005) review the various methods for counting the number of cycles within earthquake motions.

For this study these parameters are calculated:

$$D = C\sum_{i=1}^{2n} u_i^c$$

$$N_{cy} = \frac{1}{2}\sum_{i=1}^{2n}\left(\frac{u_i}{u_{\max}}\right)^c$$

where u_i is the amplitude of the *i*th half cycle, u_{max} is the amplitude of the largest half cycle and n is the total number of cycles. C and c are application-dependent damage coefficients; C is a linear scale factor and c determines the relative importance of different amplitude cycles. As adopted by Hancock & Bommer (2005), in this study c=2 and C=1 have been used. Three measures of the number of effective cycles, N_{cy}, and three measures of the cyclic damage parameter, D, (relative to 1m/s^2) have been calculated. These are those based on:

- rainflow counting, which counts both high- and low-frequency cycles in broad-banded signals;
- peak counting, including non-zero crossings; and
- peak counting, excluding non-zero crossings.

2.3. METHOD OF SELECTION

The geographical scope of VEDA is France although it is hoped that the results obtained will be useful for the definition of fragility curves for use in other countries. Metropolitan France has a seismic hazard that is thought to be characterised by earthquakes of magnitudes (M_L) less than or equal to 6.3 (except for distant earthquakes occurring in the Italian Apennines) (Marin et al., 2004). Therefore accelerograms from small and moderate earthquakes with magnitudes less than about 6.3 are most appropriate for this project. In addition, Marin et al. (2004) consider that the average focal depths in France are less than or equal to 12km. In view of this, the CD ROM of strong-motion records developed by Ambraseys et al. (2004) has been chosen as the source of data for this project since it provides a large set of data mainly from moderate (M_w<6.5) shallow (h<30km) earthquakes that occurred within Europe and the Middle East. The data provided by Ambraseys et al. (2004) has also been thoroughly validated within various projects leading up to the publication of the CD ROM of Ambraseys et al. (2004) and consequently it provides a reliable source of data. Finally, the strong-motion records contained within the databank of Ambraseys et al. (2004) have been individually processed using bandpass filters based on the signal-to-noise ratio of the record and therefore the acceleration, velocity and displacement time-histories should be free of noise within the passband of the filters used.

Another constraint that is important for future use of the fragility curves developed in VEDA is that the strong-motion parameters used to characterise the intensity of the ground motions can be predicted with accuracy when conducting an earthquake risk assessment using the fragility curves. In principle, this means that reliable and consistent (with respect to the seismotectonics of metropolitan France and the magnitude and distance range considered) ground motion estimation equations (GMEE) (e.g. Douglas, 2003) for the prediction of the chosen strong-motion parameters must be available. This reduces the number of possible strong-motion parameters that can be used to select the set of records since GMEEs are not available for many of the parameters listed above (e.g. $SLOPE_{75}$ and a_{rms}). Some parameters can be estimated by combining together predictions from a number of GMEEs, for example SI can be assessed by using GMEEs for S'_v for different periods. Illustration 3 summarises the availability of GMEEs for the strong-motion parameters identified above as possibly being useful for the selection of strong-motion records.

Strong-motion parameter	Reliable and consistent GMEE?
PGA	Yes
PGV	Yes
PGD	Yes
S_d	Yes
I	Yes
AI	Yes
A_{95}	Yes
$SLOPE_{75}$, $SLOPE_{95}$	No
NED	No [Ambraseys & Douglas (2003) present an equation for the estimation of this parameter but is only valid for M_s≥5.8, d_f≤15km]
SI	Yes (by combining other GMEEs)

Strong-motion parameter	Reliable and consistent GMEE?
ASI	Yes (by combining other GMEEs)
τ_{BA}	No
τ_{UA}	No
τ_{SA}	No
τ_{BR}	No
τ_{UR}	No
τ_{SR}	Yes
a_{rms}	No
T_m	Yes
N	No [equations have been published, e.g. Liu et al. (2001), but they have mainly been derived for use in liquefaction analysis]

Illustration 3 : Summary of which strong-motion parameters have associated reliable and consistent GMEE

In order that the ground motions selected for VEDA correspond to the typical earthquake scenario used for earthquake risk assessments in metropolitan France strong-motion records from earthquakes with $5.3 \leq M_w \leq 6.3$, $d_e \leq 30$km and focal depths≤30km were considered. A lower magnitude limit of 5.3 is used since earthquakes with magnitudes less than about 5.3 are unlikely to cause damage to structures in France unless they are very poorly constructed. This leads to a subset of the databank of Ambraseys et al. (2004) of 105 records (210 horizontal components). Due to the long run times of the numerical models, 210 components, however, is still too many to use all as input to the structural models. Therefore an additional selection procedure must be employed.

The selection procedure proposed here is to use a two-level factorial technique where for each strong-motion parameter selected records are chosen to fall within two intervals: either high or low value bins. Illustration 4 graphically shows the approach for three strong-motion parameters. One record is chosen to be at each corner of the cube. This experimental design then allows the effect of each strong-motion parameter on the damage sustained to the structure to be investigated but also the interaction effects due to the combined effects of two parameters, for example amplitude and duration.

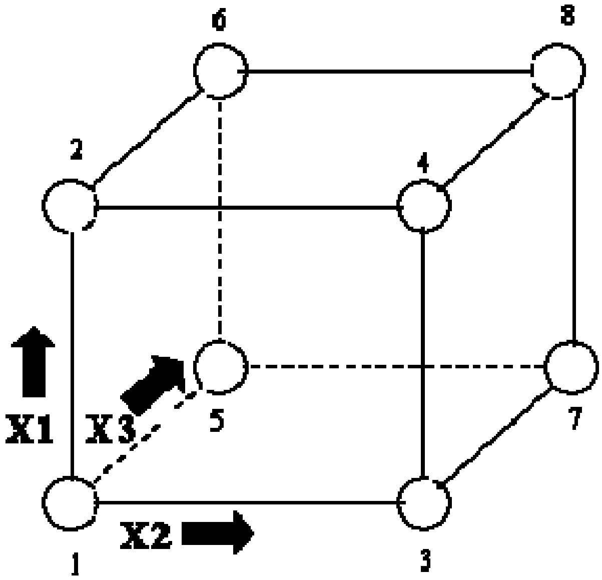

Illustration 4 A 2^3 two-level, full factorial design with factors X1, X2 and X3. Arrows show increasing values of the factors (from http://www.itl.nist.gov/div898/handbook/pri/section3/pri3331.htm).

A full factorial run consisting of two-levels for each strong-motion parameter becomes large with only a few strong-motion parameters required (e.g. 2^6=64 records for six strong-motion parameters). In addition, it is important to produce a number of sets of strong-motion records in order that the variability due to the uncontrolled factors can be studied. One type of experimental design that can reduce the required number of records is a fractional factorial design. This choice assumes that interaction effects can be neglected. Most commonly used fractional factorial design is one that uses only half the amount of experiments. Since 2^3=8 records is about the maximum possible for each experiment since it is necessary to undertake repeat experiments, this leads to a maximum choice of four strong-motion parameters. In addition, the choice of more strong-motion parameters would cut up the available data too much and would make it impossible to find records for each corner of the cube and consequently some bins would be empty.

Unlike parameters for amplitude or duration, pure measures of the frequency content such as T_m or T_p will not cause a monotonic increase in damage with increasing values of the parameter. For example, holding other characteristics of the motion constant an increase in amplitude of ground motions will invariably lead to an increase in damage hence it can be used as a measure of the seismic intensity along the x-axis of fragility curves. However, an increase in T_m holding other characteristics constant does not necessarily increase the damage but its effect will depend on the natural period of the structure and other structural parameters. Thus it is not useful to develop fragility curves using pure frequency content measures to characterise the seismic intensity.

As yet the natural periods of the structures analysed within VEDA are not known therefore it is not possible to choose spectral parameters at periods expected to be important to the structure (for example, the periods at the natural periods of the structures).

Bommer et al. (2006) find that duration and the effective number of cycles within ground motions are, in general, very poorly correlated. Therefore it would be useful to select strong-motion records with varying durations and numbers of effective cycles in order to investigate the effect of both these ground-motion characteristics on the structural damage. However, since there are currently no useable GMEEs to predict number of cycles of earthquake ground motions, number of cycles is not chosen as a strong-motion parameter for the selection procedure. At Imperial College, work is currently being undertaken to develop GMEEs for the prediction of duration (using numerous definitions) and also number of effective cycles (again using numerous definitions). Once published these GMEEs will make it useful to investigate the utility of these strong-motion parameters for developing fragility curves.

Aochi & Douglas (2006) present a table (their Table VII) listing the correlation coefficients between a number of strong-motion parameters based on the data of Ambraseys et al. (2005), which is similar to the databank of Ambraseys et al. (2004). They find that relative significant duration using the interval between 5 and 95% of total Arias intensity is very weakly correlated to PGA, PGV, AI and S_a at periods from 0.1 to 2.0s. In addition, a GMEE exists for the prediction of this parameter (Abrahamson & Silva, 1996). Hence it is a good choice of parameter for characterising the duration of earthquake ground motions for VEDA.

Aochi & Douglas (2006) also find that AI is quite strongly correlated with amplitude measures: PGA, PGV and S_a at periods from 0.1 to 2.0s (correlation coefficients between 0.60 and 0.80). Therefore it is not an ideal choice as a selection strong-motion parameter but it does measure the energy input into the structure and also has been found to be useful for the prediction of structural damage in earlier studies (e.g. Bommer et al., 2004). However, it was found that within the dataset used here that due to the high correlation between AI and S_d at 0.1 and 1.0s it was not possible to find strong-motion records within every bin.

PGA and response spectral ordinates are also strongly correlated especially at short periods. Aochi & Douglas (2006) report correlations between PGA and S_a between 0.63 (for 2.0s) and 0.93 (for 0.1s). However, the combination of two amplitude measures at two separated periods provides a measure of both the amplitude and frequency content of a strong-motion record.

Chapman (1999) shows that I is highly correlated with S'_v except at short periods (<0.2s). Therefore it is not useful to consider both I and elastic response spectral ordinates for strong-motion record selection.

Sarma & Yang (1987) find that A_{95} and PGA are well correlated. Hence it is not useful to use both these measures to choose strong-motion records.

One computationally-intensive method for choosing the subset of strong-motion parameters to use to select the set of records is to compute the correlations between all considered parameters and select those that are the most weakly correlated. This procedure has not be followed here.

2.3.1. Chosen strong-motion parameters to undertaken the selection

Based on the discussion above, Illustration 5 lists the strong-motion parameters chosen to undertake the selection of records for the CD ROM along with the minimum and maximum values of these parameters within the set of records with $5.3 \leq M_w \leq 6.3$, $d_e \leq 30$km and focal depths≤30km and the ranges of the low and high bins used for selecting the records. The ranges of the low and high bins were chosen in order to have sufficient numbers of records within each bin. A more powerful test of which strong-motion parameters are useful for estimating damage would be obtained if the ranges of the bins used was minimised so that the scatter in the strong-motion parameters within each bin was reduced. However, due to the limited amount of data this was unfortunately not possible so large ranges had to be adopted.

Parameter	Minimum	Maximum	Low bin range	High bin range
S_d at 0.1s for 5% damping	0.0035cm	0.37cm	≤0.03cm	≥0.03cm
S_d at 1.0s for 5% damping	0.059cm	16.7cm	≤0.5cm	≥0.5cm
τ_{SR}	2.56s	24.48s	≤10s	≥10s

Illustration 5 : Strong-motion parameters and ranges of low and high bins used for selecting records. Also given are the minimum and maximum values of the strong-motion parameters in the subset of Ambraseys et al. (2004) used.

The databank of records was searched to find records that fall within the different bins. Within each bin a random record from those within the bin was chosen to form part of the strong-motion selection. Since only three strong-motion parameters are used to undertake the selection the fractional factorial approach described above does not need to be followed. This will also allow the investigation of interaction effects between different characteristics of the motions. Hence sets of eight strong-motion records were selected for each independent input dataset. It was possible to find four independent sets of eight records using this approach. The selected records are listed in Appendix 1.

3. Associated CD ROM

3.1. DATA CONTAINED ON CD ROM

The accompanying CD ROM contains four sets of eight strong-motion records chosen using the method proposed in Chapter 2. These multiple sets are useful for computing the uncertainty in the observed damage computed using the structural models with these inputs. There will be differences between the results obtained using the multiple sets due to differences in the distribution of records with respect to the selected strong-motion parameters within each bin but also due to other characteristics of the motion not modelled fully by the selected strong-motion parameters.

3.1.1. Strong-motion parameters

In order that correlations between damage and strong-motion parameters not used to select the time-histories can be examined, the CD ROM contains calculated values of the strong-motion parameters listed in Section 2.2. These other strong-motion parameters could be used to derive fragility curves if it is found that they provide better correlation with damage than the parameters used to select the records. However, this would then require GMEEs to be developed to allow there use in future risk assessments.

The number of effective cycles within the selected strong-motion records were computed using the program GrndCycleDurCalc.for (J. Hancock, 2006, written communication). Other strong-motion parameters were computed using programs developed in this workpackage by the author of this report.

3.2. STRUCTURE OF CD ROM

The CD ROM provides a set of uniformly-formatted ASCII files containing corrected time-histories containing acceleration, velocity and displacement time-histories of 4 x 8=32 strong-motion records. These have been organised into four directories containing sets of eight records.

In order to aid with the use of the files within numerical models there is a directory on the CD ROM entitled ‘subroutines’ that contains Fortran and Matlab subroutines for reading in the files.

The CD ROM also contains directories containing elastic, inelastic constant strength, inelastic constant ductility and absolute input energy spectra.

In addition, the CD ROM provides a Microsoft Excel spreadsheet listing the strong-motion records contained on the CD ROM along with their associated event, path and site parameters plus computed strong-motion parameters.

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Appendix 1

List of strong-motion records selected

This annex lists the four sets of eight records chosen as input to the structural models.

Date	Time	M_w	d_e/ d_f (km)	Station	Waveform	S_d(0.1s) bin	S_d(1.0s) bin	τ_{SR} bin
26/09/1997	00:33	5.7	24/22	Monte Fiegni	000597x	Low	Low	Low
26/09/1997	09:40	6.0	27/23	Monte Fiegni	000598y	Low	Low	High
04/06/1998	21:36	5.5	15/-	Irafoss	005085y	Low	High	Low
26/09/1997	00:33	5.7	25/23	Bevagna	000595y	Low	High	High
18/05/1988	05:17	5.4	20/12	Argostoli-OTE	001862y	High	Low	Low
11/05/1984	10:41	5.5	15/13	Atina-Pretura Terrazza	000990y	High	Low	High
15/09/1976	09:21	6.1	14/9	San Rocco	000147y	High	High	Low
15/09/1976	09:21	6.1	11/8	Buia	000151y	High	High	High

Illustration 6 Strong-motion records in selection #1. d_e is epicentral distance and d_f is distance to the surface projection of the rupture (when known).

Date	Time	M_w	d_e/ d_f (km)	Station	Waveform	S_d(0.1s) bin	S_d(1.0s) bin	τ_{SR} bin
04/11/1993	05:18	5.4	18/-	Aigio-OTE	000577x	Low	Low	Low
11/05/1984	10:41	5.5	16/13	Atina	000382y	Low	Low	High
04/06/1998	21:36	5.5	23/-	Reykjavik-Heidmork (Jadar)	005089x	Low	High	Low
26/09/1997	00:33	5.7	25/23	Bevagna	000595x	Low	High	High
11/09/1976	16:31	5.3	15/-	Forgaria-Cornio	000114x	High	Low	Low
26/09/1997	00:33	5.7	27/24	Matelica	000601x	High	Low	High
07/09/1999	11:56	6.0	20/10	Athens-Papagos	001711y	High	High	Low
26/09/1997	09:40	6.0	22/17	Castelnuova-Assisi	000600x	High	High	High

Illustration 7 Strong-motion records in selection #2. d_e is epicentral distance and d_f is distance to the surface projection of the rupture (when known).

Date	Time	M_w	d_e/ d_f (km)	Station	Waveform	S_d(0.1s) bin	S_d(1.0s) bin	τ_{SR} bin
04/06/1998	21:36	5.5	15/-	Irafoss	005085x	Low	Low	Low
26/03/1998	16:26	5.5	17/13	Gubbio	000359x	Low	Low	High
07/09/1999	11:56	6.0	18/8	Athens-Syntagma	001713y	Low	High	Low
25/02/1994	02:30	5.4	12/-	Vasiliki-Town Hall	001990y	Low	High	High
03/10/1997	08:55	5.3	13/-	Nocera Umbra-Salmata	000771y	High	Low	Low
16/12/1990	15:45	5.5	15/-	Bogdanovka	000488x	High	Low	High
11/05/1984	10:41	5.5	6/2	Villetta-Barrea	000384x	High	High	Low
07/05/1984	17:49	5.9	5/	Atina	000365y	High	High	High

Illustration 8 Strong-motion records in selection #3. d_e is epicentral distance and d_f is distance to the surface projection of the rupture (when known).

Date	Time	M_w	d_e/ d_f (km)	Station	Waveform	S_d(0.1s) bin	S_d(1.0s) bin	τ_{SR} bin
16/12/1990	15:45	5.5	20/-	Akhalkalaki	000487x	Low	Low	Low
19/09/1979	21:35	5.9	23/21	Spoleto	000247x	Low	Low	High
16/12/1990	15:45	5.5	15/-	Bogdanovka	000488y	Low	High	Low
11/09/1976	16:31	5.3	9/-	Buia	000116x	Low	High	High
10/06/1987	14:50	5.4	17/9	Kyparrisia-Agriculture Bank	001900x	High	Low	Low
19/09/1979	21:35	5.9	23/21	Spoleto	000247y	High	Low	High
06/10/1997	23:24	5.6	5/-	Colfiorito-Casermette	000651x	High	High	Low
11/05/1984	10:41	5.5	15/13	Atina-Pretura Terrazza	000990x	High	High	High

Illustration 9 Strong-motion records in selection #4. d_e is epicentral distance and d_f is distance to the surface projection of the rupture (when known).

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