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Interaction ground-structure with space variability (operator DYNA_ISS_VARI)

Summary:

This document is a theoretical note describing the developed methods in the operator DYNA_ISS_VARI. This operator allows to deal with problems of interaction ground-structure (ISS) in seismic analysis where one wishes to take account of the space variability of the incidental seismic field. Within the framework of a standard seismic study with interaction ground-structure using the chaining *Code_Aster*/MISS3D, one supposes that the seismic excitation does not vary spatially. However, space variability can have considerable effects on the answers of the structures subjected to an earthquake. One observes in particular a reduction of the answer in translation what can make it possible to release from the margins in calculations of ISS.

DYNA_ISS_VARI allows to calculate the answer of a structure subjected to a variable seismic movement in space starting from a function of coherence, matrix of impedance and seismic force. These last can be calculated by software MISS3D. More precisely, one builds the spectral vectors of modal answer (exits of a spectral decomposition of the matrix of coherence) via a harmonic calculation in generalized components. At exit, one obtains the spectral concentration of the modal answer (for a unit excitation) or the temporal answer (in acceleration).

Contents

1 Introduction

In seismic calculations with interaction ground-structure, the common practice consists in considering a movement of uniform free field in any point of the surface of the ground. The recent observations of strong movements on seismographic networks however revealed space variations on rather weak scales. The taking into account of the space variability of the incidental field led to a filtering of the translatory movements for the high frequencies. The introduction of space variability can thus lead to reduced spectra of floor.

The calculation of the answer is done in three stages:

- Calculation of the generalized matrices of the structure embedded on the interface.
- Determination of the matrices of impedance of interface and the seismic force by MISS3D: Software MISS3D rests on a method of under-structuring. The field of study is broken up into under-fields - in our case ground and the structure - coupled between them by interfaces. One applies a method of resolution multi-fields and only the interfaces between fields require to be with a grid by finite elements of border. This makes it possible to model the structure (building) as well as the loadings which are applied to him entirely by *Code_Aster*. Code MISS3D, as for him, makes it possible to determine the impedances of interface between ground and structure as well as the seismic force exerted by the incidental field on the level of the interface. The resolution of the problem of dynamics and postprocessing are carried out again with *Code_Aster*.
- Resolution of the problem of dynamics on reduced basis (resulting from the under-structuring) in the field as of frequencies (`DYNA_ISS_VARI`) and postprocessing.

2 Description of the order DYNA_ISS_VARI

The operator DYNA_ISS_VARI [U4.53.31] allows to calculate the answer of a structure subjected to a variable seismic movement in space starting from a function of coherence, matrix of impedance of interface and the seismic force. These last can be calculated using the chaining *Code_Aster*/MISS3D, cf [U2.06.07]. At exit of DYNA_ISS_VARI, one obtains, in generalized coordinates, the spectral concentration of answer or a temporal answer to a temporal excitation.

More precisely, one builds the spectral vectors of modal answer (exits of a spectral decomposition of the matrix of coherence) via a harmonic calculation in generalized components. Then, one determines the spectral concentration of power (DSP) of the modal answer or the temporal answer in generalized components.

The results which one can get by using the order DYNA_ISS_VARI (for the cases with or without space variability) are the following:

- Calculation of transfer transfer functions between the seismic excitation and the answer of the structure (the transfer transfer functions are obtained by choosing an excitation by white vibration).
- Calculation of the spectral concentration of answer for the case where the seismic excitation is given by a spectral concentration (the spectrum of Kanai–Tajimi is generally used to describe the seismic excitation, to also see [R4.05.02]).
- Calculation of the temporal answer in generalized components. The simulation of a realization of temporal answer then makes it possible to determine spectra of floor.

2.1 Seismic analysis with ISS in the field of the frequencies

Software MISS3D is founded on a frequential resolution side ground; it makes it possible to determine the matrices of impedances as well as the seismic force with the interface. The problem of interaction ground-structure amounts solving on the interface the equation of harmonic dynamics:

$$\Big[\underbrace{K_b+i\omega C_b-\omega^2 M_b}_{\text{Equation d'équilibre du bâtiment}}+\underbrace{K_s(\omega)}_{\textit{Impédance d'interface sol}}\Big]q(\omega)-\underbrace{f_s(\omega)}_{\text{Force sismique}}=0 \qquad (1)$$

In the equation (1), $q(\omega)\in\mathbb{C}^m$ is the vector of the generalized unknown factors describing displacement.

In calculations of ISS with MISS3D, one must provide a accélérogramme in free field. The transform of Fourier of this signal and the matrix of impedance calculated by MISS3D make it possible to determine the seismic force in the field of the frequencies, $f_s(\omega)$.

For what follows, one defines the complex transfer transfer function in displacement $H(\omega)\in Mat_{\mathbb{C}}(m,m)$ like:

$$H(\omega)f_s(\omega)=q(\omega) \qquad (2)$$

If the excitation is supposed to be a Gaussian stationary stochastic process, then the answer is also a Gaussian stationary stochastic process. This is true because the transfer transfer function is a linear filter. Thus, one can write the relation between the spectral concentrations of the seismic force and the answer:

$$H(\omega)S_f(\omega)H^*(\omega)=S_q(\omega) \qquad (3)$$

Where H^* indicate the combined complex transposed of H and S_f is the matrix of spectral concentration of the seismic force which can be evaluated from L achievements of the temporal seismic force $f_s^l(t)$:

$$S_f(\omega)=\frac{1}{2\pi}\frac{1}{L}\sum_{l=1}^{L}f_s^l(\omega)f_s^l{}^*(\omega) \quad \text{where} \quad f_s^l(\omega)=\frac{1}{\sqrt{T}}\int_0^T f_s^l(t)e^{-i\omega t}\,dt \qquad (4)$$

In this expression, T indicate the time interval and $W(t)=1/\sqrt{(T)}$ is the natural window on $[0,T]$ (cf. [bib10]). It is about an estimator not skewed of the spectral concentration [bib10].

Notice :

One can also write:

$$S_f(\omega)=\lim_{T\to\infty}\frac{1}{2\pi T}E\left(f_s(\omega)f_s{*}(\omega)\right)$$

where $E(\cdot)$ *appoint the operator expectation.*

2.2 Taking into account of space variability

DYNA_ISS_VARI is founded on a probabilistic description of the incidental seismic field by its spectral concentration of power (DSP). The latter is generally built using a specific spectrum and of a function of space coherence. Thus, the crossed spectral concentration of the movement of the ground in free field is written:

$$S_u(x,x',\omega)=\gamma(x,x',\omega)S_0(\omega) \tag{5}$$

Where $\gamma(x,x',\omega)$ is the function of coherence of the seismic signal between two points x and x' and $S_0\in\mathbb{R}$ is the specific spectral concentration of the seismic movement in free field. It is supposed here that the spectral concentration is defined on the interval $\Omega=[-\omega_s,\ +\omega_s]$ and that it is worthless apart from this beach of frequencies. If one discretizes compared to the space variable, x and x', one obtains the matrix of following spectral concentration:

$$S_u(\omega)=\boldsymbol{\gamma}(\omega)S_0(\omega)\ \in\mathrm{Mat}_{\mathbb{C}}(m,m) \tag{6}$$

In this expression, $\boldsymbol{\gamma}$ (of dimension $m\times m$) indicate the matrix of coherence and one notes his components $\boldsymbol{\gamma}_{ij}(\omega)=\gamma(x_i,x_j,\omega)$. Elements of $S_u(\omega)=[S_{ij}(\omega)]\in Mat(m,m)$ are the crossed spectral concentrations, $S_{ij}(\omega)=S(x_i,x_j,\omega)$, m being the number of points of space discretization. In general, it is supposed that the incidental seismic field is homogeneous, i.e. the stochastic description of the field depends only on the distance, $d=|x-x'|$, but that it is independent of the space position.

The calculation of the seismic answer is based on the spectral decomposition of the matrix of coherence $\boldsymbol{\gamma}(\omega)$. Let us specify that it is about a spectral decomposition compared to the space variable and not compared to variable time. Thus, one a:

$$S_u(\omega)=\Phi(\omega)\Lambda(\omega)\Phi{*}(\omega)S_0(\omega) \tag{7}$$

Where Φ is a matrix containing the clean vectors φ_k matrix of coherence $\boldsymbol{\gamma}$ and Λ is the diagonal matrix containing the eigenvalues, $\Lambda=diag(\lambda_k),\ k=1,\ldots m$. Thereafter, one will speak about modes POD (Orthogonal Proper Decomposition) to indicate them φ_k. This makes it possible to distinguish them from the mechanical modes. From the expression of the equation (7), one defines:

$$s_u^k(\omega)=\varphi_k(\omega)\sqrt{\lambda_k(\omega)}\sqrt{S_0(\omega)},\quad\forall\,\omega\in\Omega \tag{8}$$

Knowing that $S_u(\omega)=\sum_{k=1}^{m}s_u^k(\omega)s_u^k{*}(\omega)$. The spectral concentration of the seismic force is obtained starting from the movement with the interface of the ground by the transfer transfer function $G(\omega)$ matric:

$$S_f(\omega)=G(\omega)S_u(\omega)G{*}(\omega) \tag{9}$$

And as follows:

$$s_f^k(\omega)=G(\omega)\varphi_k(\omega)\sqrt{\lambda_k(\omega)}\sqrt{S_0(\omega)},\quad \forall\,\omega\in\Omega \tag{10}$$

In the studies of ISS with *Code_Aster*, the transfer transfer function $G(\omega)$ is calculated by MISS3D, this is described more in detail in the section §2.2.1.
The expression (10) is the entry for the traditional seismic analysis, to see equation (7). The model is “reduced” if one can truncate expression (10) with $K\leq m$ modes POD.
As one has just seen it, the calculation of the seismic forces with space variability of the incidental field implies a spectral decomposition of the matrix of coherence $\boldsymbol{\gamma}$. For the continuation of calculations, one retains only one reduced number of modes POD, namely $K\leq m$ modes. The parameter precision gives the share of “the energy” of the matrix which one preserves by retaining only one reduced number of vectors and eigenvalues of $\boldsymbol{\gamma}$. If one indicates by K the number of modes POD selected (one retains them K greater eigenvalues), one a:

$$\text{precision}=\frac{\sum_{i=1}^{K}\lambda_i^2}{\sum_{i=1}^{M}\lambda_i^2} \tag{11}$$

The value of $0{,}999$ by default for the precision is taken.

2.2.1 Functions of coherence

The function of coherence depends on the distance from separation d between two points x and x' and of the frequency. In general, one expresses it by a term of module and a term of phase:

$$\gamma(d,\omega)=|\gamma(d,\omega)|\exp(-i\theta(\omega,d)) \tag{12}$$

The term $\exp(-i\theta(\omega,d))$ represent the dephasing of at various times of arrival of the waves. The term of amplitude corresponds to “the pure inconsistency”. It can be evaluated starting from the DSP (autospectres and interspectres) at the points x and x' :

$$|\gamma(d,\omega)|^2=\frac{S(\omega,x,x')^2}{S(\omega,x)S(\omega,x')} \tag{13}$$

Currently available functions of coherence in `DYNA_ISS_VARI` are the function of coherence of Mita&Luco and the function of coherence of Abrahamson (for the rock). One does not introduce a term of phase.

The function of coherence of Became moth-eaten & Luco [bib5, bib6] is written:

$$\gamma(d,f)=\exp\left[-\left(\frac{\alpha\,\omega\,d}{v_s}\right)^2\right] \tag{14}$$

In this expression, v_s is the propagation velocity of wave HS (typically $200-1000\ m/s$) and the parameter α can vary $0{,}1$ with $0{,}5$ according to the cases but is generally taken equal to $0{,}5$. If one chooses $\alpha=0.0$, then one carries out a calculation without space variability.
It is seen that the length of correlation for the function of coherence of Became moth-eaten and Luco [bib5, bib6], is characterized by the expression $(\omega\,\alpha/v_s)^{-1}$.
The function of generic coherence of Abrahamson [bib9] is written, for $\omega=2\pi f$:

$$\gamma(d,f)=\left[1+\left(\frac{f\tanh(a_3 d)}{f_c\,a_1}\right)^{n1}\right]^{-0.5}\left[1+\left(\frac{f\tanh(a_3 d)}{f_c\,a_2}\right)^{n2}\right]^{-0.5} \tag{15}$$

With the following values of the parameters for the horizontal movement:

$$\begin{aligned} f_c &= -1{,}886+2{,}221\ln(4000/(d+1)+1{,}5) \\ n_1 &= 7{,}02 \\ n_2 &= 5{,}1-0{,}51\ln(d+10) \\ a_1 &= 1{,}647 \\ a_2 &= 1{,}01 \\ a_3 &= 0{,}4 \end{aligned} \quad (16)$$

The function of coherence of Abrahamson for a rock or an average ground (EPRI 1015110.2007) is written, for $\omega=2\pi f$:

$$\gamma(d,f)=\left[1+\left(\frac{f\tanh(a_3 d)}{f_c(d)\,a_1}\right)^{n1(d)}\right]^{-0.5}\left[1+\left(\frac{f\tanh(a_3 d)}{a_2}\right)^{n2}\right]^{-0.5} \quad (17)$$

For the rock, one has the following values of the parameters for the horizontal movement:

$$\begin{aligned} f_c &= 27{,}9+4{,}82\ln(d+1)+1{,}24(\ln((d+1)-3{,}6))^2 \\ n_1 &= 3{,}8-0{,}04\ln(d+1)+0{,}0105(\ln((d+1)-3{,}6))^2 \\ n_2 &= 16{,}4 \\ a_1 &= 1{,}0 \\ a_2 &= 40 \\ a_3 &= 0{,}4 \end{aligned} \quad (18)$$

This function of coherence is an empirical model readjusted starting from the 78 recorded earthquakes with Pinyon Flat (the USA) by Abrahamson. It is also used for other soil types for which it is regarded as conservative.

For the average ground, one has the following values of the parameters for the horizontal movement:

$$\begin{aligned} f_c &= 14{,}3+2{,}35\ln(d+1) \\ n_1(d) &= 2 \\ n_2 &= 15 \\ a_1 &= 1{,}0 \\ a_2 &= 15{,}8-0{,}044\,d \\ a_3 &= 0{,}4 \end{aligned} \quad (19)$$

2.2.2 Modeling of the seismic forces with *Code_Aster*

Case of a rigid foundation

The modes of interface are the six modes of rigid body. The modal seismic force calculated by MISS3D is written then for a unit excitation (white vibration):

$$f_s(\omega)=K_s(\omega)x_0 \quad (20)$$

Where $K_s(\omega)$ is the matrix of modal impedance and $x_0=(1.,0.,0.,0.,0.,0.)$ for a seismic excitation in direction x, $x_0=(0.,1.,0.,0.,0.,0.)$ for a seismic excitation in y and $x_0=(0.,0.,1.0.,0.,0.,0.)$ for a vertical earthquake. The seismic force is nonworthless only for the modal component in the direction of the earthquake (x,y,z). In the same way, the function of coherence is built only for the degrees of freedom of translation in the direction of the earthquake. The other degrees of freedom are not affected.

To take account of space variability, one determines the modal participation for each mode POD characterizing space variability:

$$f_s^k(\omega)=K_s(\omega)\Theta^T s_u^k \quad (21)$$

Where Θ is the matrix containing the modes (mechanical) of interface.

Case of a flexible foundation

The modes of interface are them $d\times 6$ unit modes relative to d nodes of the interface. The modal seismic force calculated by MISS3D is written then:

$$f_s(\omega)=K_s(\omega)x_0 \quad (22)$$

x_0 is the vector of modal participation comprising of 1 for degrees of freedom relating to the direction of the earthquake and the zeros for the other directions. In the same way, the seismic force and the function of coherence are nonworthless only for the degrees of freedom in the direction of the earthquake. One builds the matrix of coherence and then the vectors s_u^k for the degrees of freedom in the direction of the earthquake :

$$f_s^k(\omega)=K_s(\omega)s_u^k \quad (23)$$

Case of an "unspecified" foundation

In these cases, correspondent either with an inserted foundation, or with a case of interaction ground-fluid-structure, or with a case where the modes of interface are unspecified modes different of unit modes relating to the nodes of the interface, the vector of modal participation x_0 is not any more itself unit, nor independent of the frequency and there is not any more identity between the physical and modal coordinates of the interface.
The modal seismic force calculated by MISS3D is written then:

$$f_s(\omega)=K_s(\omega)x_0(\omega) \quad (24)$$

$x_0(\omega)$ the vector of modal participation is thus obtained by inversion of the seismic force $f_s(\omega)$ compared to the impedance of ground $K_s(\omega)$; the physical vector on the interface corresponding $X_0(\omega)$ is written then: $X_0(\omega)=\Theta x_0(\omega)$ where Θ is the matrix containing the modes (mechanical) of interface.
To take account of space variability, one determines the physical contribution on the interface for each mode POD characterizing space variability:

$$X_u^k(\omega)=X_0(\omega)s_u^k \quad (25)$$

The physical vector on the interface $X_u^k(\omega)$ corresponds to a vector of modal participation $S_u^k(\omega)$ such as: $X_u^k(\omega)=\Theta S_u^k(\omega)$ where Θ is the matrix containing the modes (mechanical) of interface.
Then the corresponding seismic force will be expressed thus :

$$f_s^k(\omega)=K_s(\omega)S_u^k(\omega) \quad (26)$$

2.2.3 Calculation of transfer and DSP transfer functions of answer

By linear filtering, one obtains:

$$s_q^k(\omega)=H(\omega)s_f^k(\omega) \quad (27)$$

What makes it possible to rebuild the matrix of spectral concentration of answer like:

$$S_q(\omega)=\sum_{k=1}^{K\le m} s_q^k\ (s_q^k)* \quad (28)$$

The model is reduced if one can truncate expressioN (28) with $K\le m$ modes POD.
For an excitation by white vibration, one directly obtains the DSP of the transfer transfer function at exit.
Notice :

Without space variability the seismic field and thus the seismic force are the same ones for the whole of the nodes of the interface (the foundation):

$$S_u(x, x', \omega) = S_0(\omega)$$

Caution: In the actual position, `DYNA_ISS_VARI` can only treat the case of a shallow foundation. As for the modes of interface, one can choose between a modeling by the 6 modes of rigid body (rigid foundation), of the modes of interface unspecified (flexible foundation) and a modeling by all modes EF (flexible foundation).

2.2.4 Calculation of the temporal answer to an earthquake

In a general way, It is possible to simulate trajectories of a Gaussian stationary process which one knows the DSP by using the theorem of the spectral representation.

One could thus obtain a realization the temporal structural answer (stochastic process characterized by his spectral concentration $S_q(\omega)$) by the formula (cf. [bib4]):

$$q(t) = \sum_k \sum_{n=0}^{N_T} H(\omega_n) G(\omega_n) e^{i\omega_n t} \varphi_k(\omega_n) \sqrt{\lambda_k(\omega_n)} \sqrt{S_0(\omega_n)} \xi_n^k \sqrt{\Delta\omega} \quad (29)$$

where them ξ_n^k are complex random variables independent of reduced centered normal law and where $\Delta\omega$ indicate the step of frequency (constant), ω_n, $n=1, N_T$ are the frequencies resulting from the discretization. Under the assumption that one can approach the specific spectral concentration using a number of accélérogrammes, one a:

$$S_0^L(\omega) = \frac{1}{2\pi} \frac{1}{L} \sum_{l=1}^{L} u_0^l(\omega) . u_0^l * (\omega) \quad (30)$$

Where $u_0(\omega)$ is obtained starting from accélérogramme $u(t)$ in free field:

$$u_0(\omega) = \frac{1}{\sqrt{T}} \int_0^T u_0(t) e^{-i\omega t} dt \quad (31)$$

Here, one does not use this method of generation of signals starting from their DSP because one works with evolutionary processes whose one knows a realization, namely the accélérogramme as starter of mechanical calculation. Being given this context, one places oneself rather within a deterministic framework of filtering of signals. Thus, one introduces a deterministic filter modelling the effect of the space inconsistency. This filter is given by the matrix $\Phi(\omega)\Lambda(\omega)^{1/2}$. One can thus calculate frequency response and obtain the temporal answer by opposite FFT. Frequency response is written:

$$q(\omega) = \sum_k H(\omega) G(\omega) \phi_k(\omega \sqrt{\lambda_k(\omega)} u_0(\omega) \quad (32)$$

By considering the equation (32), one can check that the spectral concentration of the answer q is that given by L'equation (28). The model is "reduced" if one can truncate the expression (28) with $K \leq m$ modes POD.

2.3 Calculated results PaR `DYNA_ISS_VARI`

In short, the operator `DYNA_ISS_VARI` allows to get the following results:

- Calculation of the spectral concentration of the modal answer for a unit seismic excitation (in displacement). In order to obtain the answer to a seismic excitation, one multiplies the DSP obtained for a unit excitation by the spectrum modelling the excitation (Kanai–Tajimi or other).

- Calculation of the transfer transfer functions for a unit seismic excitation (in displacement). The transfer transfer functions are given by the root of the module of the auto--spectra of answer, $\sqrt{\left|\left[S_v(\omega)\right]_{ii}\right|}$ (root of the absolute value of the auto--spectrum [bib9] in physical coordinates). By comparing the transfer transfer functions with and without space variability, one can determine margins related to the inconsistency of the seismic signal (cf also [bib8]: factor of margin “inconsistency” in the seismic EPS).
- Calculation of the spectra of floor via the transitory answer (`FONC_SIGNAL` must be well informed). `DYNA_ISS_VARI` allows to calculate the transitory answer in acceleration. The spectra of answer of oscillator (SRO) for a floor can be obtained in postprocessing.

3 Other software: SASSI and CLASSI

The two tools most used to do calculations of ISS with space variability for the nuclear power are software CLASSI and SASSI. Method established in *Code_Aster* is close to that of SASSI [bib8, bib9].

Just like DYNA_ISS_VARI in *Code_Aster*, SASSI makes it possible on the one hand to determine transfer functions transfer (excitation unit) and on the other hand to calculate temporal answers taking account of space variability.
The calculation of the transfer transfer functions is done according to the same principle in the two codes (*Code_Aster* and SASSI): one carries out a spectral decomposition (POD) matrix of coherence, one determines the answer mode POD by mode POD in order to recompose of them the DSP of response as described in this note.
For the calculation of temporal answers, there is a difference between methodology SASSI and the implementation in Code_Aster. more precisely, SASSI introduces a random phase for each mode POD [bib9]:

$$q(\omega)=\sum_k H(\omega)G(\omega)\phi_k(\omega)\sqrt{\lambda_k(\omega)}\,e^{i\eta^k(\omega)}u_0(\omega) \quad (33)$$

Where them $\eta^k(\omega)$ are uniform random variables on the interval $[-\pi,\pi]$. One determines then m answers and m SRO to retain the average of it. However, the introduction of the random phase is not useful if one regards the problem as a problem of filtering (deterministic) of a deterministic signal (the accélérogramme) as described above. One can check moreover that the hope of the expression (33) is equal to the expression (32).

The method used by CLASSI is different, insofar as one remains within the framework of classical stochastic dynamics: one solves a linear problem of filtering (as it is the case for DYNA_ISS_VARI when no seismic signal is given). The DSP of the seismic excitation is directly approximate using an algorithm making equivalence between the DSP and the SRO. The SRO of answer is obtained same manner starting from the DSP of answer, namely by determining the SRO corresponding to the DSP of calculated answer [bib9].

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5 Description of the versions of the document

Version Aster	Author (S) Organization (S)	Description of the modifications
10.2	I .ZENTNER EDF-R&D/AMA	Initial text
10.4	I .ZENTNER, F.VOLDOIRE EDF-R&D/AMA	Small corrections.
13.2	I .ZENTNER EDF-R&D/AMA	Addition of the function ofAbrahamson