Deconvolution and Soil-Structure Interaction with ProMiss3D software based on seismic recordings on Hualien array

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ABSTRACT

The modelling of Soil-Structure Interaction (SSI) has become an important point for nuclear seismic engineering. More realistic considerations about embedment, soil layers characteristics and variability can provide important margins compared with simple basic design calculations.

For many years, EDF as chosen ProMiss3D software, using subdomain method with frequency resolution, for the evaluation of the seismic behavior of its nuclear buildings. Seismic recordings and Large Scale Seismic Tests (LSST) results, such as those obtained on Hualien array, are adequate data for the validation of the results given by SSI numerical calculations.

This paper presents, for the Chi-Chi earthquake event, the solicitations on different layers and the response of the building calculated with ProMiss3D and compared with Hualien data.

INTRODUCTION

In order to justify the seismic behavior of existing French Nuclear Power Plants buildings and equipments, EDF uses a Soil Structure Interaction software, ProMiss3D, that has been elaborated by coupling Miss3D SSI code, developed by D. Clouteau at LSSMat, Ecole Centrale de Paris [3] and *Code_Aster* Finite Element code developed at EDF-DRD [4], [5].

This software allows more realistic SSI calculations compared with simplified methods, like soil-springs method used for Design Spectrum calculations, as far as non-homogeneous soil layers, soil damping, embedment and flexible foundation are concerned.

Usually, tri-directional solicitations in the nuclear buildings (response spectrum, displacements, ...) are linearly calculated using :

i) a Finite Element model of the structure whose dynamic behavior is characterized by modal analysis considering clamped foundation,

ii) 3 shear waves velocity profiles for the soil layers : uncertainties about those characteristics are taken into account by enlarging the average shear wave velocity profile with $\sqrt{(2/3)}$ and $\sqrt{(3/2)}$ factors ; note that modulus reduction due to seismic distortion is also considered,

iii) 3 different free-field accelerograms per direction whose response spectra fit the Safe Shutdown Earthquake.

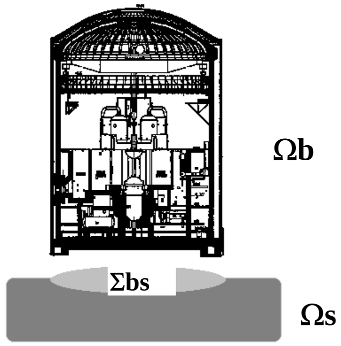
Seismic recordings and Large Scale Seismic Tests (LSST) results, such as those obtained on Hualien array, are the most adequate data for the validation of the results given by SSI numerical calculations.

ProMiss3D SOFTWARE

ProMiss3D has been built by coupling a Boundary Element Method (BEM) software, Miss3D, using subdomain method with frequency resolution, and Finite Element Method software *Code_Aster,* [3], [4], [5].

Miss3D uses a linear assumption valid for both geometry and behavior : Navier's equation (momentum conservation) is associated to Hooke's law in elastic materials. This assumption allows the application of Fourier's transform to temporal variables.

Miss3D is based on a sub-structuring method in dynamics where only the interfaces of the sub-domains require to be meshed with border finite elements (Fig. 1). The resolution of the total problem is carried out at the borders of the sub-domains and is based on the knowledge of elementary solutions : the Green's functions that allows to formalize the fields generated in an infinite domain under a specific solicitation. It can be extended to infinite domains, by avoiding any reflection on fictitious borders truncating the soil domain. Miss3D also allows the treatment of laminated domains without needing to mesh their interfaces.



Ωb : building domain
Σbs : building-foundation interface
Ωs : soil domain

Fig 1. Subdomain decomposition used in ProMiss3D.

The resolution of the dynamic multi-domain problem can be rather simplified by separating the displacement solution into (i) a part not taking into account of the interface connections and (ii) a part taking into account these connections (only true for a linear resolution). The resolution of this total problem is done in two correlated phases:

- the study of the local problems where local balance is checked on each substructure, independently on the others and without taking into account the interface connections. For each subdomain, the equation of the dynamic problem under the effect of seismic incidental fields is solved by taking into account external forces and internal forces acting on the considered substructure;
- the study of the coupling problem implies to check the continuity of the displacements and the reciprocity of the efforts on the interface. The problem of the interface connections, solved without taking into account external forces and internal forces acting on the subdomains, makes it possible to obtain the stress balance on the interface. The integration of these stresses leads to additional terms of impedance and variable seismic forces.

Thus a Soil-Structure Interaction problem, with its boundary conditions (continuity of displacements and reciprocity of the efforts at the interface), can be reduced on the interface to the following frequency-dependent equation (1) :

$$\left\{\mathbf{K_b} - \mathbf{i}\omega\,\mathbf{C_b} - \omega^2\mathbf{M_b} + \mathbf{K_S}(\omega)\right\}\mathbf{q} - \mathbf{f_i}(\omega) = \mathbf{0} \qquad (1)$$

where:

- $\mathbf{K_b}$, $\mathbf{C_b}$, $\mathbf{M_b}$ are the stiffness, damping and mass matrices of the building obtained from the FE model;
- ω is the pulsation,
- $\mathbf{K_S}(\omega)$ is the ω-dependent impedance matrix of the layered soil,
- $\mathbf{q}$ are the generalized coordinates of the system ,
- $\mathbf{f_i}$ are the ω-dependent forces due to the seismic excitation .

LARGE SCALE SEISMIC TESTS ON HUALIEN ARRAY

An international research program on SSI has been carried out between 1992 and 2002 in order to record the natural seismic solicitations on and around a ¼ scale reactor building built near Hualien, Taiwan [1]. The soil instrumentation around the building is displayed on Fig. 2. Each accelerometer has recorded about 100 tri-directional natural seismic motions between 1994 and 2000.

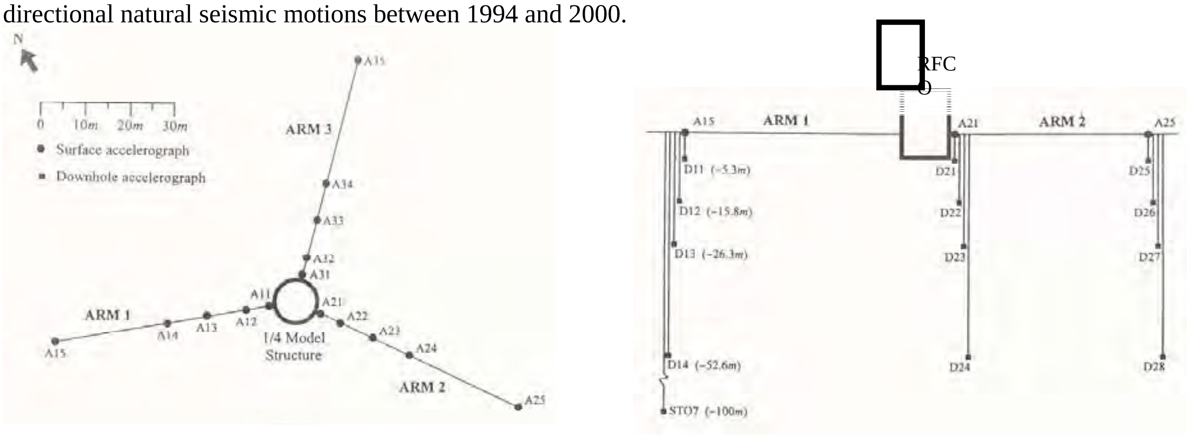


Fig. 2 Soil Instrumentation of the Hualien array

The Chi-Chi earthquake that occurred at 17h47 the 20th of September 1999, produced horizontal free field accelerations that reached 0.12g on the test array (event n°38). Its magnitude was M_L=8.0 and the epicentre was located at 82km from the site. The accelerations recorded at the different stations during this event will be used for free-field input and for comparison to the results.

The motions are recorded with a 5ms step for a duration that can reach 110s. In order to reduce computation times, the step of the input accelerograms is set to 10ms (100 Hz) and the duration is reduced to 40.96s. The East-West acceleration recorded at station A25 is plotted on Fig. 3.

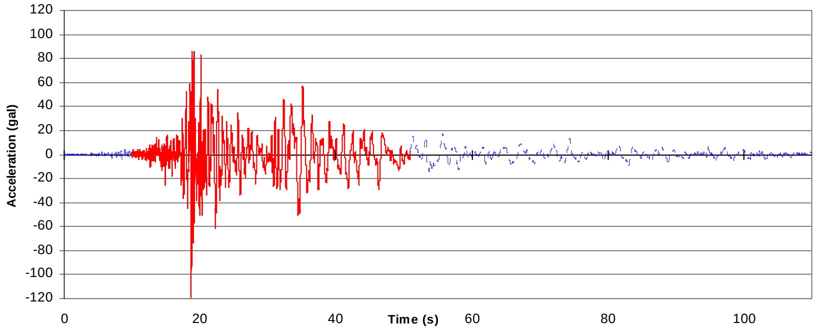


Fig. 3 EW acceleration recorded at station A25 (10s-50.96s duration used for calculations)

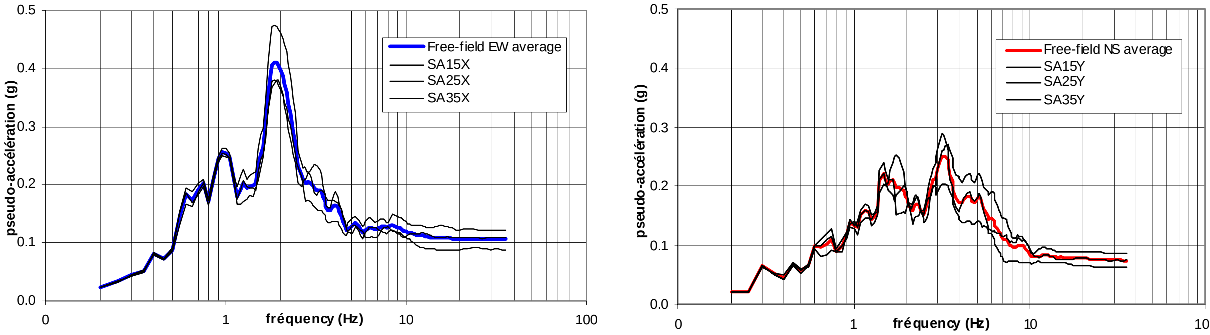


Fig. 4 Variability in the signals recorded at free field stations A15, A25 and A35 for EW direction (left) and NS direction (right) – 5% damping Response Spectrum

HUALIEN 1/4TH SCALE REACTOR BUILDING

The FE model used for this study has been developed for [6] and is presented on Fig. 5. Its dimensions are 10.8m large and 16.1m height. The basement and the roof are meshed with 3D elements and the cylindrical wall is meshed with 0.3m thick shells. The elements size is about 1m. The total mass of the structure is 1400 t, including 654t for the basement.

The embedment of the building is 5m; in terms of boundary conditions, contact was considered between the basement and the soil but no contact between the cylindrical wall and the soil, see Fig. 5.

The concrete of the building is modelled with the following characteristics : Young's Modulus E=28220 MPa, density d = 2.4 t/m^3, Poisson's ratio ν = 0.16.

The modal analyse with clamped foundation leads to 10.3Hz main horizontal frequencies and 30Hz vertical frequency.

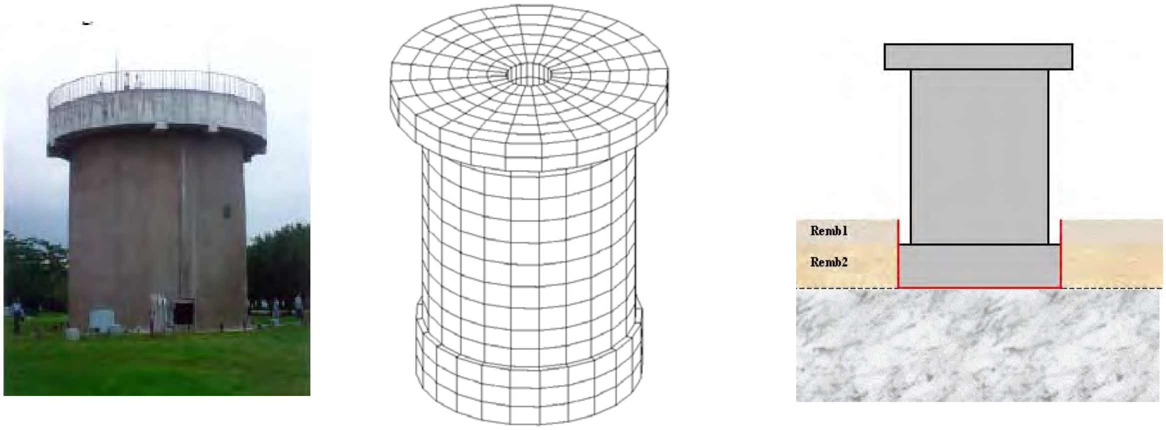


Fig. 5 Views of the real structure (left), the mesh (middle) and the contact boundary conditions (right)

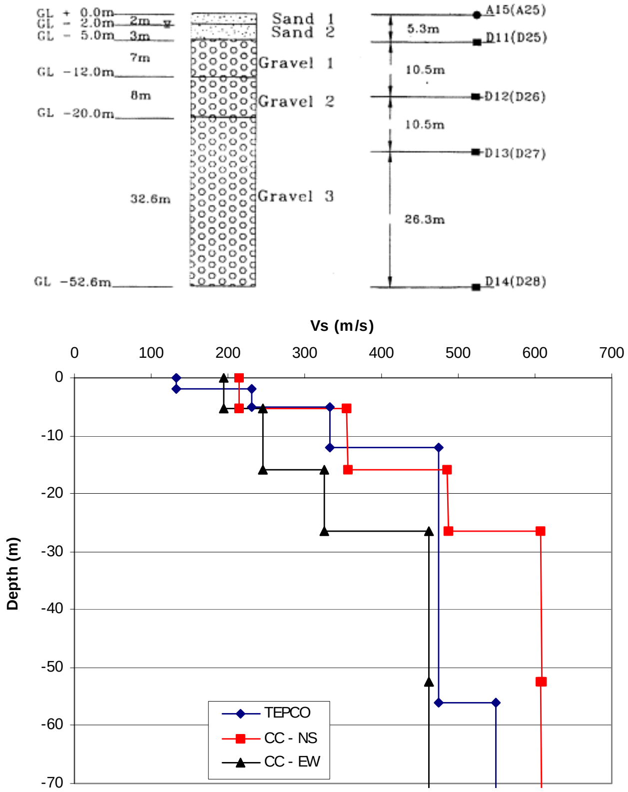
SOIL DATA

The geological profile of Hualien LSST site is shown on left part of Fig. 6. The right part shows the different depths of the embedded stations. It is mainly composed by sands on the first 5m and gravels up to 52.6m depth. The Hualien soil was at least as extensively analysed as any nuclear power plant site : a lot of soil characterization surveys have been conducted in order to define the shear wave velocity profile under the structure.

The distribution of shear wave velocities have been established by TEPCO [1] from a geophysical survey (P–S logging) before the structure to be built. This initial low distortion profile is plotted on Fig. 6.

In 1998, Chen, C.H., and Chiu, H.C., worked on the characterization of the soil anisotropy based on the signals recorded at embedded stations during six earthquakes (whose magnitudes where higher than 4.5) that occurred on the site between 1994 and 1995 [2]. By calculating transfer function between the different stations, they proposed two different shear waves velocity profiles for East-West and North-South direction. These profiles are considered to be "best estimate" as horizontal anisotropy and soil distortion during earthquake are taken into account. We then considered both profiles, called CC-EW and CC-NS, for the realistic calculations with ProMiss3D, as shown in Fig. 6.

Soil internal damping is set to 5%, which is a typical regular value for such soft soils. All ProMiss3D calculations are made considering a linear behavior of soil layers and building.



CC - EW

Layer	Depth (m)	ρ (kg/m3)	ν	Vs (m/s)	E (MPa)	ξ (%)
1	5.3	1810	0.43	194.5	196	5
2	15.8	2420	0.47	244	424	5
3	26.3	2420	0.47	327	761	5
4	52.6	2420	0.47	462	1519	5
5	SUBS	2420	0.47	462	1519	5

CC - NS

Layer	Depth (m)	ρ (kg/m3)	ν	Vs (m/s)	E (MPa)	ξ (%)
1	5.3	1810	0.43	214	237	5
2	15.8	2420	0.47	356	902	5
3	26.3	2420	0.47	486	1680	5
4	52.6	2420	0.47	608	2630	5
5	SUBS	2420	0.47	608	2630	5

TEPCO

Layer	Depth (m)	ρ (kg/m3)	ν	Vs (m/s)	E (MPa)	ξ (%)
1	2	1690	0.38	133	83	5
2	5	1930	0.48	231	305	5
3	12	2420	0.47	333	789	5
4	56	2420	0.47	476	1612	5
5	SUBS	2420	0.47	550	2152	5

Fig. 6 Soil composition and shear waves velocity profiles (left) – Soil characteristics from [2] and [1] (right)

RESULTS

For both soil profiles, CC-EW and CC-NS, three tri-directional ProMiss3D calculations are made using successively A15, A25 and A35 stations recordings as free-field input. For each direction and each soil profile, 3 Response spectra are then calculated at the roof of the building (RFC) and at control points located at depths -5.3m and -15.8m, far from the building,.

The variability of the free field input signals is illustrated by the 5% damping response spectra plotted on Fig. 4.

For each horizontal direction, the average of the 6 response spectra (2 soils x 3 free-field inputs) is compared with the response spectrum of the station accelerogram. Reference response spectrum at -5.3m is calculated with the average of D11, D21 and D25 stations recordings. Reference response spectrum at -15.8m is calculated with the average of D12, D22 and D26 stations recordings.

The 5% damping response spectra are plotted on Fig. 7 to 10.

Considering peak values and Zero Period Acceleration, average response spectra calculated at the top of the building are in good accordance with the recorded solicitations. A 50% overestimation can be observed for EW direction at 4Hz frequency, corresponding to SSI frequency that seem to be most amplifying in the calculations (left part of Fig. 7).

In the vertical direction, there is no significant amplification, as shown on Fig. 8.

The accelerations calculated at control points at -5.3m and -15.8m fit perfectly the recordings, except in EW direction where the 2 Hz peak is 30% underestimated.

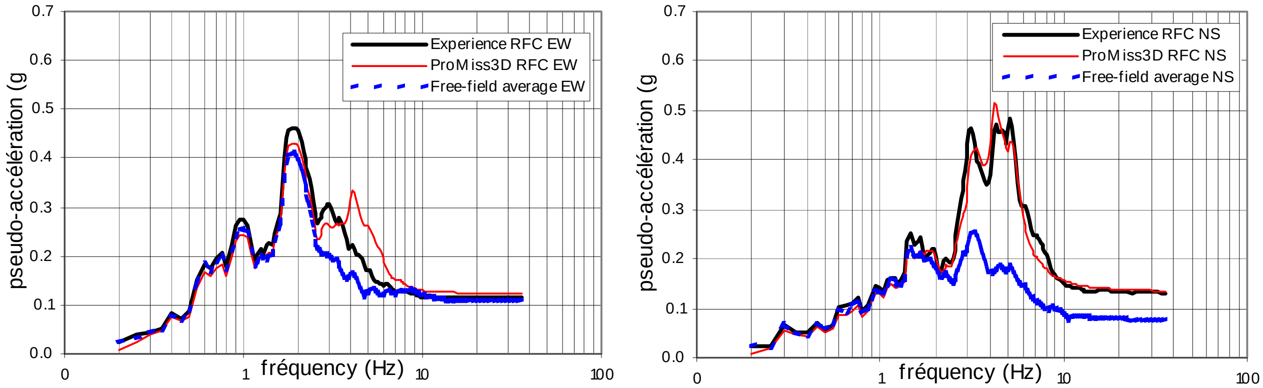


Fig. 7 Comparison of EW (left) and NS (right) Response Spectra at the roof of the building (RFC)

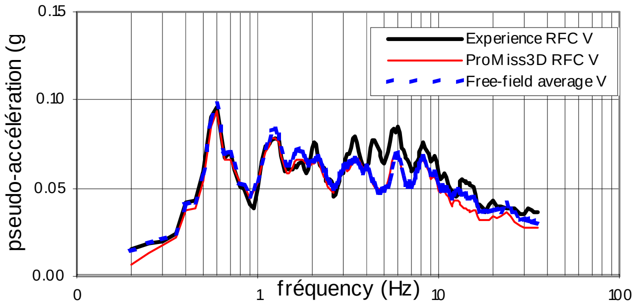


Fig. 8 Comparison of Vertical Response Spectra at the roof of the building (RFC)

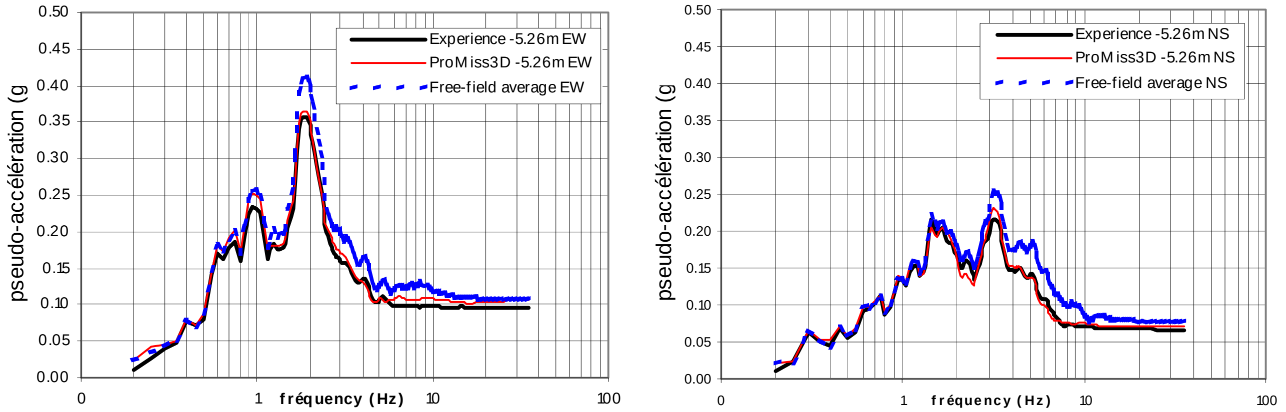


Fig. 9 Comparison of EW (left) and NS (right) Response Spectra at -5.3m

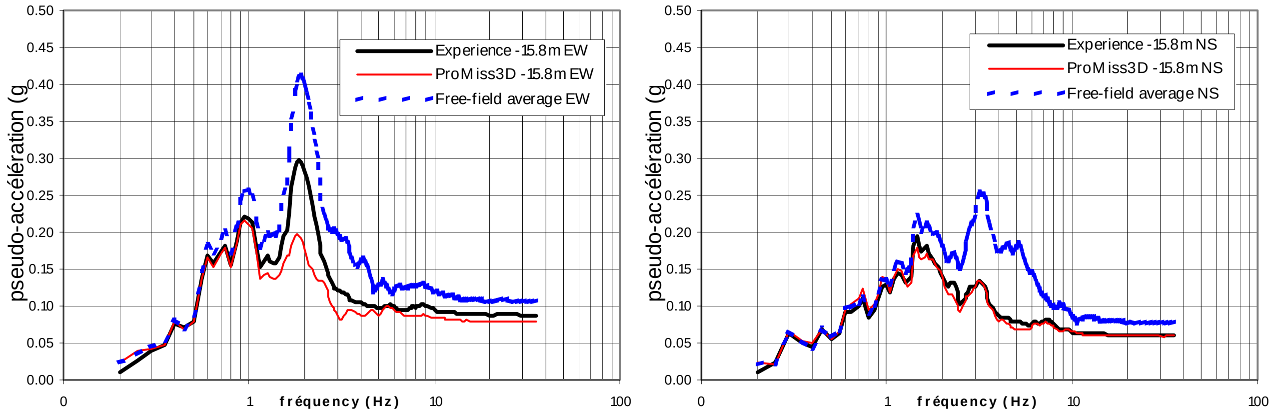


Fig. 10 Comparison of EW (left) and NS (right) Response Spectra at -15.8m

CONCLUSION AND PERSPECTIVES

Free field Hualien accelerations, recorded during the Chi-Chi earthquake that occurred at 17h47 the 20th of September 1999, have been used as input for best estimate SSI calculation with ProMiss3D software.

The shear wave velocity profiles, published by C.H. Chen and H.C. Chui [2] and taking into account layers anisotropy et soil distortion, was also considered.

The results obtained show that :

- (i) Average response spectra calculated at the top of the building and at different depths are in good accordance with the signals recorded during the earthquake
- (ii) The 2 profiles from [2] seems to be well adapted to represent the variability of soil characteristics for strong motions earthquakes at Hualien site.

Further developments and investigations are also purchased with ProMiss3D, in order to extend its domain of validity with phenomenon such as Structure-Soil-Structure Interaction, spatial incoherency of incident field, probabilistic calculations and local variability of soil layers.

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