ONDA 1.4

USER'S MANUAL Version 1.4

by

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1 INTRODUCTION ONDA

This user's manual describes how to use a newly developed computer code for performing One-dimensional Non-linear Dynamic Analysis (ONDA) of soil deposits. The code has been developed by revisiting the work by Ohsaki (1982) and extending its capabilities to model important aspects of soil non-linear response when subjected to earthquake loading like for instance the phenomenon of cyclic degradation. In the Ohsaki model a horizontally stratified soil deposit is idealized as a discrete mechanical system composed by a finite number of lumped masses connected with a series of springs and dashpots. Non-linearity is modeled by assuming 1) a "backbone" curve that describes the initial, monotonic loading of the stress-strain curve, and 2) a "rule" that simulates the unloading-reloading paths and stiffness degradation undergone by soil as seismic excitation progresses.

Typically, the backbone curve is obtained from conventional cyclic undrained loading laboratory tests. For the "rule" it is generally used the so-called "Masing criterion" which assumes that the unload-reload branches of the stress-strain curve have the same shape of the initial loading curve but affected by a scale factor (*n*) equal to 2. ONDA assumes a modified 2nd Masing criterion, which considers a scale factor (*n*) not necessarily equal to 2. It turns out that a factor *n* greater than 2 allows to simulate the phenomenon of cyclic hardening, while cyclic softening can be modeled by assuming values of n smaller than 2. This generalization of the Masing criterion allows to proper simulate the phenomena of soil hardening and soil degradation giving to ONDA the capability to compute the permanent shear strains developed during a seismic event. Description of the procedure required to evaluate the model-parameters is also given in the manual.

In ONDA the numerical solution of the non-linear equations of motion is obtained using the unconditionally stable Wilson θ algorithm (with θ >1.37).

The version 1.0 of the code has been developed by Camelliti (1999) and assume the n parameter arbitrarily but constant. Version 1.0 has been used in some applications

(Vercellotti 2001, De Martini Ugolotti 2001, Saviolo 2002). The version 1.3 (Lo Presti et al. 2003) offers the possibility of selecting initial values of the *n* parameter and its variation with strain and number of cycles.

The actual version 1.4 in addiction gives the possibility to select α and R parameters.

2 One-Dimensional Ground Response Analysis

One-dimensional ground response analysis introduces some restrictive hypotheses on geometry and wave field kinematics, which are discussed in this chapter. Nonetheless these restrictions, 1D analyses have been successfully used in many cases and more specifically: a) when topographic irregularities are absent, b) when the effects of the boundaries of the sedimentary valleys or of deeper geologic structures can be neglected.

2.1 Geometry and kinematics assumptions

One dimensional ground response analyses are based on the following assumptions:

- horizontally stratified soil layers;
- soil strata and bedrock extend infinitely in the horizontal direction;
- the only waves traveling into the soil deposits are SH waves propagating vertically from the underlying bedrock.

2.2 Input motion, bedrock and outcropping motion

Figure 1 recalls common accepted terminology to define ground motion. The main objective of seismic response analysis is the analytical determination of the free surface motion, i.e. the motion at the surface of a soil deposit. The motion at the base of the soil deposit (top of the bedrock) is called bedrock motion. The rock outcropping motion is the motion at a location where bedrock is exposed at the ground surface.

In the case of infinitely stiff base, bedrock and rock outcropping motions coincide. In the case of compliant base, these motions do not coincide because of radiation damping in the rock. The way of considering compliant base (i.e. radiation condition) in ONDA is described in the sequel.

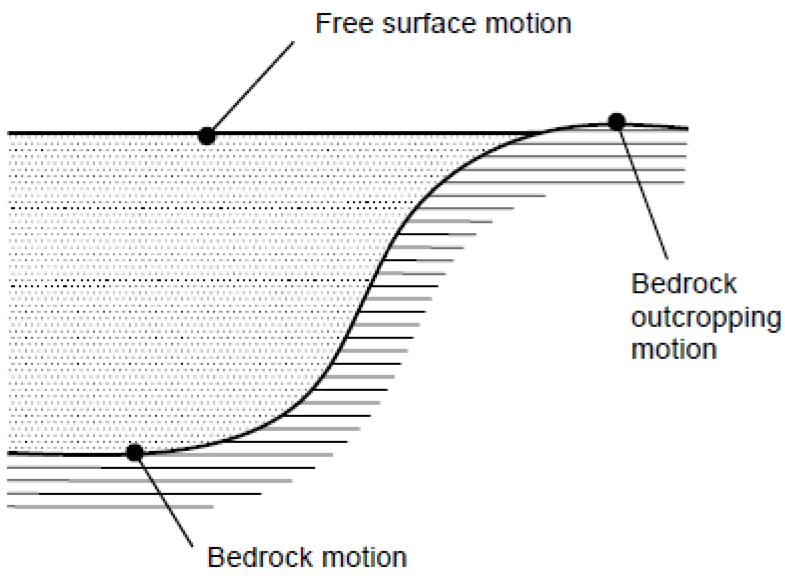

Figure 1 Ground response nomenclature

3 THE PROGRAM ONDA

3.1 General features of the code

ONDA is a computer code designed to perform one-dimensional non-linear ground response analysis of horizontally stratified soil deposits. The code has been developed following the model by Ohsaki (1982) where the soil deposit is modeled as a discrete system composed by a finite number of lumped masses connected weakly with springs and dashpots (see Fig 2). Weak coupling among the lumped masses yields a characteristic three-diagonal, banded stiffness and a consistent mass matrix (Ohsaki, 1982). The equation of motion governing the vibrations of the discrete system subjected to a base acceleration $\ddot{y}$ can be written as follows:

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = -\ddot{\boldsymbol{y}}\boldsymbol{M} \cdot \boldsymbol{r} \tag{1}$$

where **x** is the horizontal displacement vector (see Fig. 2), **r** is a unit vector, **M** is the consistent mass matrix formed by terms proportional to $\rho_j H_j$ with ρ_j being the mass density of the j^{th} layer having thickness H_j and $j = 1, N$. **C** is the Rayleigh damping matrix, and **K** the stiffness matrix formed by terms proportional to G_j/H_j with G_j being the strain dependent shear modulus associated to the j^{th} layer. **N** is the number of sublayers in which the soil deposit has been subdivided. Further details on the structure of the stiffness and damping matrices appearing in Eq. (1) with the precise definition of the elements $K_{i,j}$ and $C_{i,j}$ are provided in Oshaki (1982) and will not be reported here. The input motion is assigned at the base of the mechanical system (see Fig. 2c) where the bedrock is assumed to have a finite stiffness. The radiation condition in the half-space as well as the possibility that the input motion be assigned as an outcropping motion is modelled through the standard concept of *energy-transmitting boundary* (Joyner and Chen, 1975; Oshaki, 1982). This essentially consists in inserting at the base of the soil deposit a fictitious dashpot with damping coefficient equal to $\sqrt{\rho_b G_b}$ where ρ_b and G_b are the mass density and the tangent shear modulus of the sub-stratum. Equation (1) is non-linear because of the strain dependence of the elements of **K**. It was solved by integration in the time domain using the Wilson θ-method, which is recalled to be unconditionally stable for $\theta > 1.37$ (Chopra, 1995).

The program ONDA computes the time history of acceleration, relative velocity and relative displacement at a specific sub-layer (either outcropping or not), the corresponding Fourier and elastic response spectra, the time history of stress, strain and stress-strain loops at a specified sub-layer (either outcropping or not), and the horizontal permanent deformations undergone by a specific sub-layer (either outcropping or not) at the end of the seismic excitation.

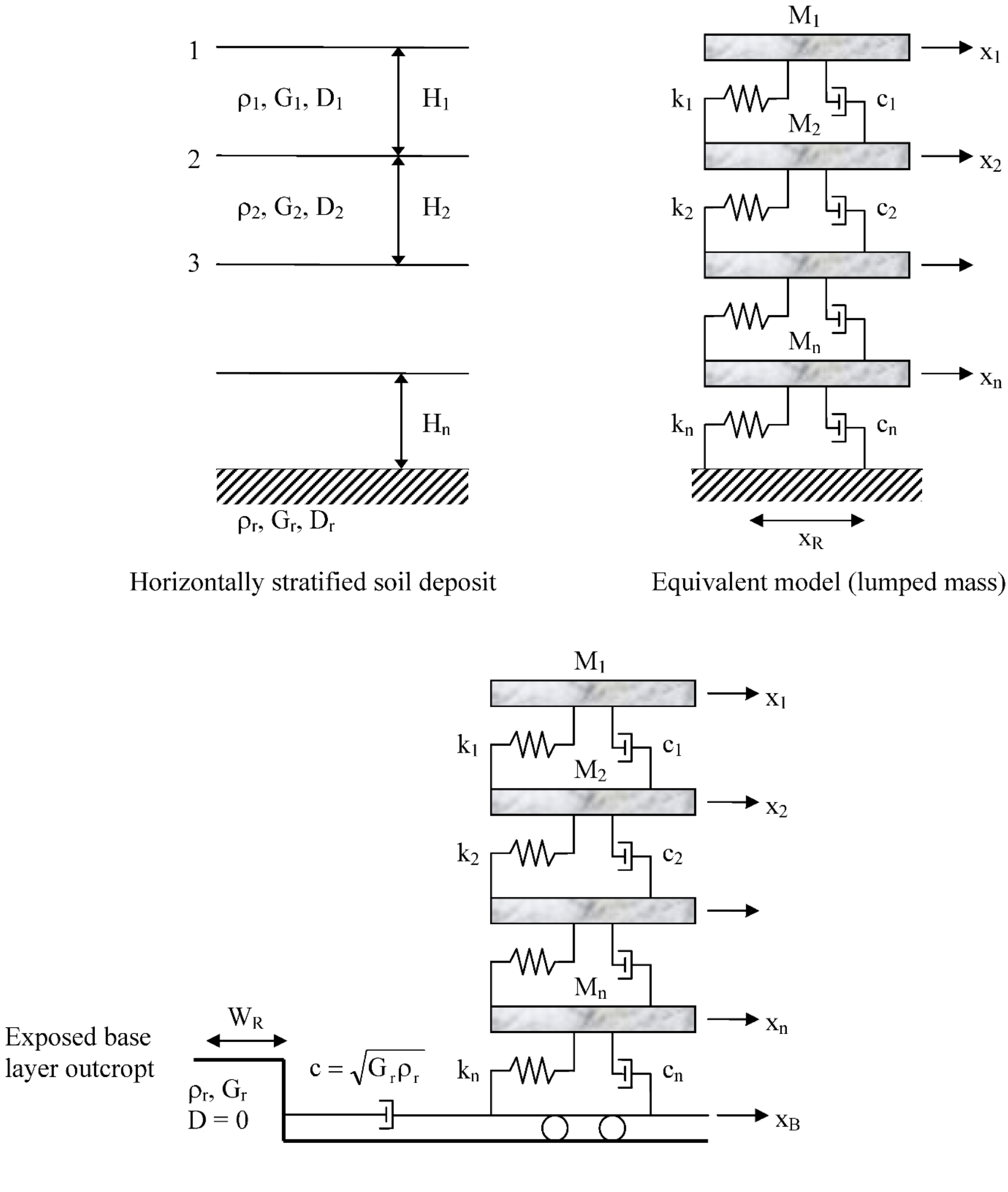

Figure 2 Discrete system

3.2 Non-linear cyclic constitutive modeling

The constitutive model adopted by ONDA employs for the description of the initial loading stress-strain curve (backbone or skeleton curve) the Ramberg-Osgood (1943) model. The cyclic behaviour of unloading-reloading (hysteretic curves) has been modelled using the *modified second Masing criterion* (Tatsuoka et al., 1993) (see Fig. 3). Such a criterion represents the most innovative aspect of the constitutive model and hence of the computer code.

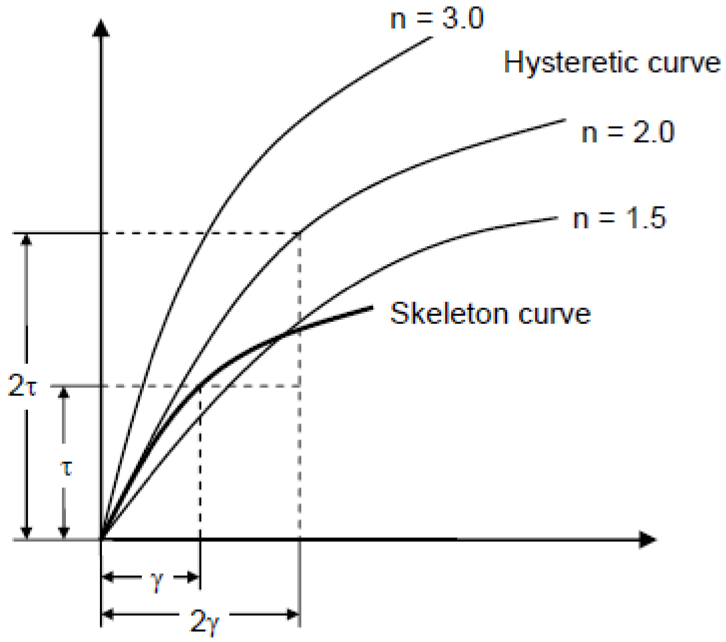

Figure 3 Geometrical formation of hysteretic curve

It will be described in the sequel. Firstly it is worthwhile to resume the three basic rules that are assumed for the non-linear model:

- 1st rule: the stress-strain curve is the backbone curve until the appearance of the first stress reversal;

- 2nd rule: the stress-strain curves (hysteretic curves), after the stress-reversal, follow the modified second Masing criterion;
- 3rd rule: beyond the terminal point of a hysteretic curve, the stress-strain curve follows the second latest hysteretic curve. The stress-strain curve resumes the backbone curve in two special cases: a) when the latest curve is the backbone curve and b) when the second latest curve is the backbone curve. This third rule coincides in practice with the additional criteria postulated by Pyke (1979).

The expression of Ramberg-Osgood (1943) is represented by a non-invertible power relation depending on four parameters. The parameters α and R describe position and curvature respectively. The other parameters are τ_{max} (soil shear strength) and G_0 (the low-strain shear modulus). For fine-grained soils, τ_{max} can be determined from the undrained shear strength[1]. The relation can be written as follows:

$$x = y \cdot (1 + \alpha \cdot |y|^{R-1}) \tag{2}$$

where x and y are the normalized strains and stresses respectively. In particular, $x = \gamma/\gamma_{RIF}$ and $y = \tau/\tau_{max}$. In these definitions τ is the shear stress, γ is the engineering shear strain, $\gamma_{RIF} = \tau_{max}/G_0$.

The parameters α and R of Eq. (2) are determined from a regression on experimental data obtained from a monotonic loading test or the first quarter of cycle of cyclic tests. The parameter τ_{max} can be experimentally determined from laboratory tests as α and R. The parameter G_0 can also be determined from laboratory tests if there is availability of high quality samples. However, it is recommended to obtain G0 from in situ geophysical tests.

The Ramberg-Osgood (1943) model associated to the Masing (1926) criteria allows representing the unloading-reloading branches of the stress-strain relationship as follows:

$$\frac{x - x_c}{n} = \frac{y - y_c}{n} \cdot \left[1 + \alpha \cdot \left|\frac{y - y_c}{n}\right|^{R-1}\right]$$

(3)

where x_c and y_c are respectively the normalized strain and stress amplitude at the loading reversal point of the stress-strain loop. In particular, according to the Masing criterion the unloading-reloading curves have the same shape as the backbone curve but they are enlarged by a *scale factor* of 2. In ONDA however, it was adopted the modified second Masing criterion (Tatsuoka et al., 1993) for which the above scale factor may virtually assume an arbitrary value *n*. In particular, to simulate cyclic hardening behavior it will be necessary to assume a scale factor $n > 2$, whereas cyclic softening or material degradation could be modeled by assuming decreasing values of n even $n < 2$. It is then possible by assuming the scale factor *n* as a function of the number of cycles *N*, and of the strain level to fully describe some of the most relevant aspects of soil non-linear behavior including those arising from the increase of pore water pressure, even though indirectly because the analysis is conducted in terms of total stresses.

If G_{eq} is the unloading-reloading shear modulus from cyclic tests, and G_s is the secant shear modulus from monotonic tests or the first quarter of cycle of cyclic tests, the specific sequence of *n* values adopted by ONDA is obtained experimentally from the condition $G_{eq} = G_s$. More precisely, the sequence of *n*-values is determined from the expression $n = 2\gamma_c/\gamma$ where γ_c and γ and are respectively the cyclic and monotonic shear strain values for which the relationship $G_{eq} = G_s$ holds (Tatsuoka et al. 1993) (see fig. 4 a, b, c).

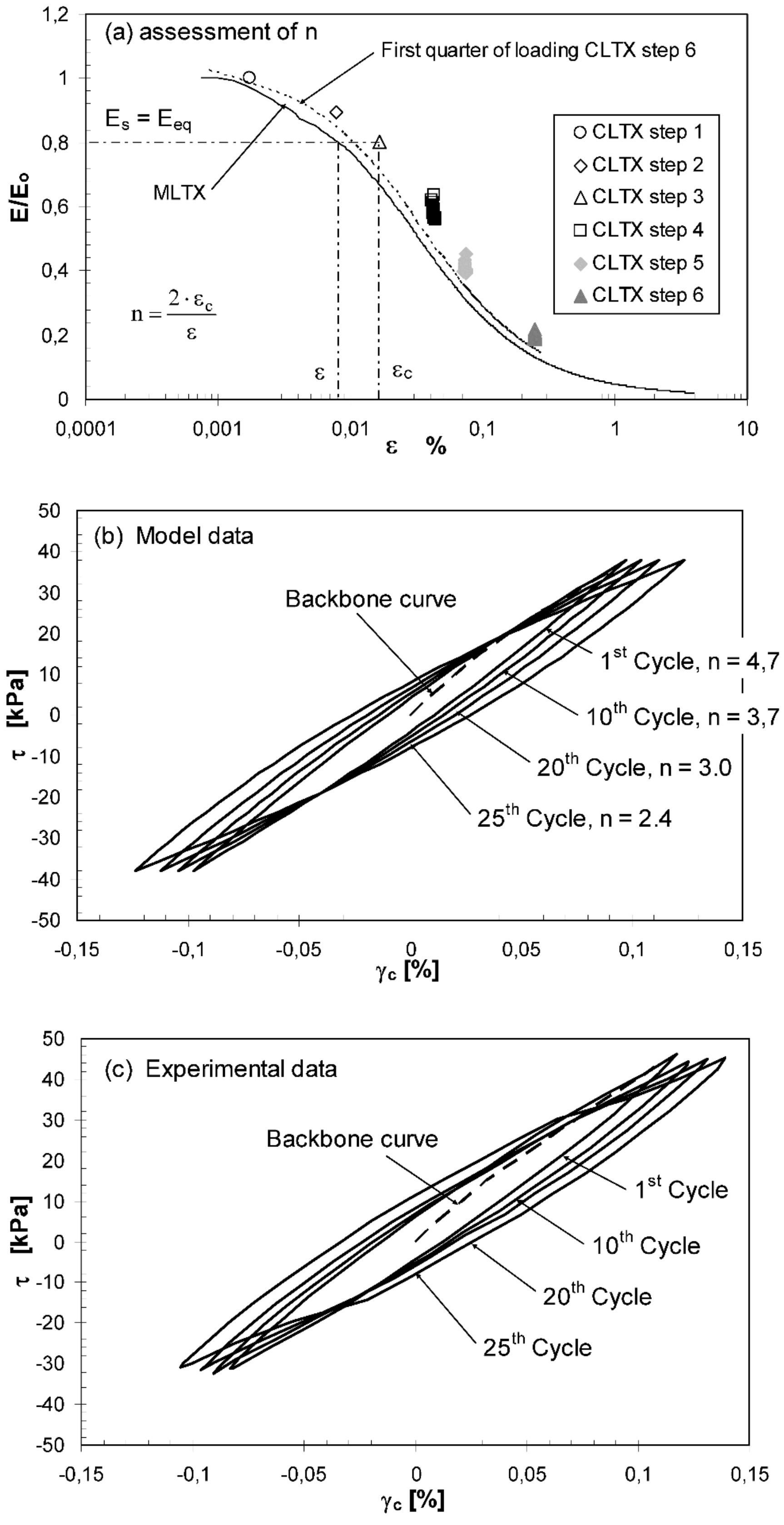

Figure 4 Assessment of n parameter (a) and comparison between model prediction (b) and experimentally determined stress strain loops (c)

It is recalled that in ONDA and in general in computer codes based on modelling the non-linear behaviour through the association of an initial loading backbone curve with a “rule” that simulate the unloading-reloading cyclic response with or without cyclic hardening or softening, the phenomenon of energy dissipation is reproduced implicitly in the analysis through the updating of the stiffness matrix **K** (see Eq. 1) as the loading history progresses (Camelliti, 1999). Such type of constitutive behavior is borrowed from the general theory hypoelasticity (Lubliner, 1990), which even though is questionable from the thermodynamical point of view, it is not the cause of too severe shortcomings in the engineering applications. This hypoelastic, built-in mechanism of energy dissipation in ONDA, is superimposed to a second mechanism which is the one associated to the damping matrix **C** of Eq. (1). Of much lesser importance, this energy dissipation mechanism is associated to a damping of a viscous nature (i.e. frequency dependent) and it is effective only at very low strain levels, below the linear cyclic threshold shear strain (Vucetic, 1994). At larger strain, this second mechanism still holds but represent a very small percentage in comparison to the hysteretic mechanism.

3.3 Spatial discretization and time integration algorithms

Horizontally stratified soil deposits are modeled as a discrete system composed by a finite number of lumped masses connected weakly with springs and dashpots (see Fig 2). Macro-layers are identified through the geotechnical profile and are characterized by a set of constitutive parameters. For the step-by-step integration of the equations of motion [1] ONDA has adopted the Wilson θ method which is unconditionally stable for $\theta \geq 1.37$ (Chopra, 1995). Details about the application of the Wilson θ method can be found in any textbook on structural dynamics and will not be reported here. At the time *t*, the equations of motion [1] can be re-written in the following incremental form:

$$\{\widehat{\boldsymbol{K}}\}_{\boldsymbol{t}}\{\boldsymbol{\Delta x}\}_{\boldsymbol{t}} = \{\boldsymbol{R}\}_{\boldsymbol{t}} \tag{4}$$

where $\{\boldsymbol{\Delta x}\}_{\boldsymbol{t}}$ is the incremental displacement vector at time *t*, and the matrices $\{\widehat{\boldsymbol{K}}\}_{\boldsymbol{t}}$ and $\{\widehat{\boldsymbol{R}}\}_{\boldsymbol{t}}$ are defined by the following relationships:

$$\{\widehat{\boldsymbol{K}}\}_t = \frac{6}{\tau^2}\boldsymbol{M} + \frac{3}{\tau}\boldsymbol{C} + \{\boldsymbol{K}\}_t \tag{5a}$$

$$\{\boldsymbol{R}\}_t = \boldsymbol{M}\cdot\left(\Delta R_t\boldsymbol{I} + \frac{6}{\tau}\{\dot{\boldsymbol{x}}\}_t + 3\{\ddot{\boldsymbol{x}}\}_t\right) + \boldsymbol{C}\cdot\left(3\{\dot{\boldsymbol{x}}\}_t + \frac{\tau}{2}\{\ddot{\boldsymbol{x}}\}_t\right) \tag{5b}$$

where $\{\boldsymbol{K}\}_t$ is the stiffness matrix of Eq.[1] updated at time t, $\boldsymbol{I}$ is the identity matrix, $\tau = \theta\cdot\Delta t$, and $\Delta R_t = -\theta(\ddot{y}_{t+\Delta t} - \ddot{y}_t)$. Once Eq.[4] is solved, the acceleration, velocity and displacement vectors $\{\ddot{\boldsymbol{x}}\}_{t+\Delta t}$, $\{\dot{\boldsymbol{x}}\}_{t+\Delta t}$, $\{\boldsymbol{x}\}_{t+\Delta t}$ at time $t+\Delta t$ can be computed by means of the following relations:

$$\{\ddot{\boldsymbol{x}}\}_{t+\Delta t} = \frac{6}{\tau^2\theta}\{\boldsymbol{\Delta x}\}_t - \frac{6}{\tau\theta}\{\dot{\boldsymbol{x}}\}_t + \left(1-\frac{3}{\theta}\right)\{\ddot{\boldsymbol{x}}\}_t \tag{6a}$$

$$\{\dot{\boldsymbol{x}}\}_{t+\Delta t} = \{\dot{\boldsymbol{x}}\}_t + \frac{\Delta t}{2}[\{\ddot{\boldsymbol{x}}\}_{t+\Delta t} + \{\ddot{\boldsymbol{x}}\}_t] \tag{6b}$$

$$\{\boldsymbol{x}\}_{t+\Delta t} = \{\boldsymbol{x}\}_{\mathrm{t}} + \Delta t\{\dot{\boldsymbol{x}}\}_t + \frac{(\Delta t)^2}{6}[\{\ddot{\boldsymbol{x}}\}_{t+\Delta t} + 2\{\ddot{\boldsymbol{x}}\}_t] \tag{6c}$$

From the knowledge of the displacement vector, the strain and the stress vectors can be straightforwardly calculated.

4 SYSTEM REQUIREMENT

- Windows XP, Windows Vista, Windows 7 or newer
- 32 or 64 bit
- Minimum 3 GB disk space to download and install

4.1 Python environment

ONDA 1.4 has been developed in Python language. The program is available in an executable format. Not preliminary installation of python is required to run ONDA 1.4.

4.2 Installing and removing ONDA

To install the application run the executable file and follow the instructions. To remove the application, go to “Control Panel” → “Programs and Features” and uninstall the application.

5 RUNNING ONDA

To perform a ground response analysis with ONDA it’s necessary to create 4 tab-delimited txt files (input data):

1. the first to load the soil profile;
2. the second to load the values of soil cohesion c’ (in kPa);
3. the third to load the values of the angle of friction φ' (in degrees);
4. the fourth to load the input motion (acceleration in g).

You can find an example of all the txt files required to perform an analysis in the "Example" folder.

The first one is a txt file containing the main properties of the soil deposit (soil profile). Below an example.

Thick [m]	Unit W. [kN/m3]	Vs [m/s]	G_0 [MPa]	Damping D_0 [-]	R [-]	alpha [-]	Tau Max [kPa]	OCR (1)	IP [%]	Label [#]
15	19	100	0	0.02	2.05	20.1	0	1	10	1
15	19	400	0	0.02	2.05	20.1	0	2	10	2
0.01	22	1200	0	0.02	0	0	0	2	10	1

The field "Label" is necessary to properly assign the values of cohesion c' (in kPa) and of angle of friction φ' (in degrees) to a specific soil layer.

For example, in the table above, has been assigned a "Label" value equal to 1 to the first soil layer and a "Label" value equal to 2 to the second layer. The txt file for the cohesion must be created writing on a single line (the first line) all the values of the cohesion separated by the 'tab'. The first cohesion value will be related to all the soil layers having a "Label" value equal to 1, the second cohesion value will be related to all the soil layers having a "Label" value equal to 2 and so on.

The same procedure is valid for the txt file necessary to import the angle of friction values.

Note: to the bedrock layer assign always a "Label" value equal to 1.

The input motion file instead must be created writing a simple txt file with a single column (the first column) containing the acceleration data in gravity (g) unit.

After start the application, press the button "Load data for each macro-stratum" in the main tab *"ONDA Analysis"* and load the text file (format: tab delimited .txt) with the soil profile properties, then press the button "Load angle of internal friction" and load the angle of friction values, then press the button “Load cohesion” and load the cohesion values and then load the input motion using the “Load accelerogram” button. After that, insert manually in the main tab *“ONDA Analysis”* the following input data:

- *Scale Factor [-]* = insert the scale factor that you want to apply to scale the input motion. Use a scale factor equal to 1 if you don’t want to scale the accelerogram used;
- *Time interval [in sec]* = the sampling time of the input motion (the accelerogram in the example folder has a sampling time equal to 0.005 sec);
- *Time interval subdivision* = insert an integer number. Equal to 1 if you want to maintain the time interval equal to the sampling time, bigger than 1 if you want to subdivide every time interval in N time sub-intervals. If you are performing a Linear ground response analysis it’s recommended to use a Time interval subdivision equal to 1; if you are performing a Non-Linear analysis it’s strongly suggested to use a bigger value (for common situations a Time interval subdivision value equal to 4 should be appropriate to obtain the convergence of the solution);
- *Number of macro-strata including the base layer* (or bedrock) = is the total number of layers in the soil profile. In the example above the number of layers is 3 (including the bedrock);
- *Water table depth [in meters]* = specify here the water table depth;
- *Type of ONDA analysis* = insert 1 if you want to perform a non-linear analysis in time domain, insert 0 if you want to perform a linear analysis;
- *Procedure for n (Masing)* = enter 1 if you want to consider *n* variable; enter 0 if you want to consider *n* constant;
- *Input Motion type* = enter 1 if the input motion is an outcrop motion; enter 0 if the input motion is a within motion;
- *Damping ratio elastic response spectrum [in %]* = specify the damping ratio value for the calculation of the elastic response spectrum;

- *Output-Result Depth [in meter]* = enter the depth at which you prefer to automatically obtain the main output plots (acceleration time history, fourier spectrum and elastic response spectrum);

Then press the "Verify Input" button to import all the values inserted manually and to check if they are correct. Finally, you can press the "Start analysis" button. If the analysis has been correctly executed the message "Analysis completed" will appear in the same row of the Start Analysis button.

Using the next tabs "Accelerogram", "Fourier spectrum", "Elastic R-Spectrum", "Strain and Displ Time History", "Peak Profiles", "Stress-Strain", "Permanent displ" and "Other Outputs", you can plot all the results of the seismic response analysis. In these tabs there are 2 "Plot" buttons. The first one called "Plot …. Viewer" works only to plot the results of an analysis already performed, using the txt files saved. The second one called "Plot ….", instead, works only to see the results obtained in the current analysis. The zoom, pan and home buttons instead works in both cases.

5.1 Input parameters: additional information

If G_0 is not defined (zero values in the fourth column of the txt file containing the main properties of the soil deposit), the values of the small strain shear modulus are computed from the shear wave velocities.

If τ_{max} is not given (zero values in the column n°8 of the txt file containing the main properties of the soil deposit), it is computed in the following way:

$$\tau_{max} = c' + \sigma_v' \cdot \tan \varphi' \tag{7}$$

where: c' and φ' are the parameters of the Mohr-Coulomb failure envelope defined by the vectors *fi* and *cp* for the different types of materials; σ_v'= vertical effective geostatic stress at middle height of each layer.

OCR and plasticity index are assumed to affect the value of the parameter *n* and its dependence on number of cycles and cyclic shear strain will be shown in the next section.

5.1.1 Constitutive parameters

To perform a ground response analysis ONDA requires the following constitutive parameters:

- the Ramberg-Osgood parameters τ_{max}, G_0, α and R to define the backbone curve.
- scale amplification factor (n) and its variation with strain level and number of cycles.

There is enough information in the literature to obtain appropriate values of the Ramberg-Osgood parameters and, in any case, it is quite easy to obtain these parameters from laboratory tests and/or in situ geophysical tests. In any case, in the following a set of α and R parameters for the backbone-curve are suggested. On the other hand, there are very few data in literature as far as the *n* parameter is concerned. Such data are briefly summarized below.

IP	**α**	**R**	**G_0/τ_{max}**
0	6.90	2.49	3169.77
15	7.14	2.37	925.74
30	5.08	2.29	501.33
50	3.44	2.18	307.14
100	2.47	2.17	172.35
200	1.82	2.06	90.54

Lo Presti et al. (1998, 2000) have compared the results of cyclic loading torsional shear tests (CLTST) or Resonant Column tests (RCT) to those of monotonic loading torsional shear tests (MLTST), both performed on the same specimen in undrained conditions. In particular, the MLTST stage was run after CLTST. A rest period of 24 hours, with open drainage, took place between two stages. The tests were run on some Italian clays of medium to high plasticity, having OCR from 1.5 to 5 and the maximum applied single amplitude shear strain was typically less than 0.05%. The above described experiments and comparisons led to values of n ranging mainly from 4 to 6.

Ionescu (1999) performed similar tests on reconstituted Toyoura sand specimens clarifying the following aspects:

- at very small strains ($\gamma \leq 0.001\%$) n is typically equal to 2;
- the value of n increases up to 6 with the increase of shear strain (not exceeding 0.05%);
- for a given strain level n increases with the number of loading cycles. Stable values of n are reached after 5 cycles.

The above reported results clearly indicate that: i) at very small strains the secant stiffness coincides with that inferred from cyclic tests, which involves a quasi-elastic behaviour at small strains (Tatsuoka and Shibuya 1992); ii) at larger strains (less than 0.05%) the stiffness from cyclic tests is greater than the secant stiffness, which involves cyclic hardening for both clays and sands (Tatsuoka and Shibuya 1992).

The results of 23 undrained cyclic triaxial tests performed on K_0 consolidated specimens have been analyzed on the purpose of obtaining more precise indication about the values of the n parameter (Rigazio 2001, Pallara and Lo Presti 2002). Test specimens were 70 mm in diameter and 140 mm in height. Apparatuses were equipped for local strain measurements. *Dry setting* method and automatic K_0 consolidation procedure with a tolerance on radial displacement of ±0.5 μm were adopted (Lo Presti et al., 1999). Cyclic loading was carried out by six steps. Each step involved 30 cycles at constant strain and strain rate (triangular wave form). The strain levels, imposed to the specimen, in the different steps, were equal to 0.003 – 0.01 - 0.02 – 0.05 – 0.1 – 0.3%. After cyclic loading, the specimen experienced a rest period of 24 hours with opened drainage. After that it was subjected to undrained monotonic loading. Most of the tested specimen were NC but some were OC with OCR in between 2 and 4.

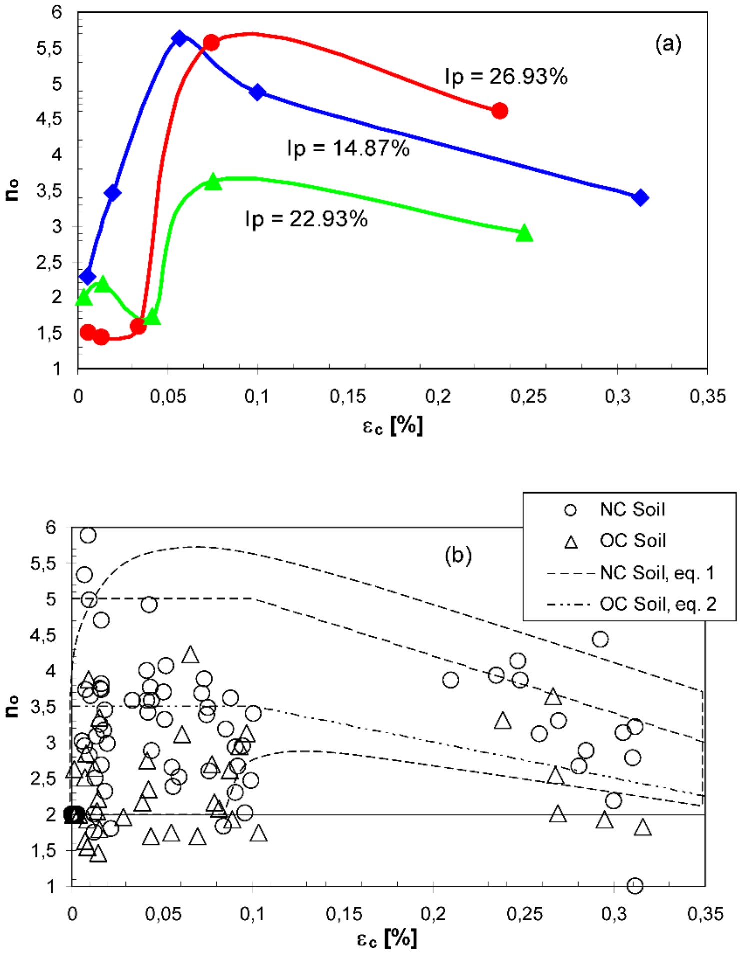

Figure 5 n_0 vs strain level: a) influence of soil type and Ip; b) influence of OCR

The secant stiffness, measured during the first quarter of cycle or from the subsequent monotonic loading, has been compared to the unloading-reloading stiffness obtained from the subsequent cycles. The following experimental evidences were established from such a comparison:

- the initial value of n (n_0) depends on strain level and the type of soil (Figures 5a and 5b). Such a parameter has been obtained by comparing the secant stiffness from first quarter of loading to that inferred from the first cycle of unloading reloading;
- at very small strains n_0 is very close to 2 (Figure 5a);
- the values of n_0 increase from 2 to a maximum value of 6 with an increase of the axial strain up to a certain value; for strain level greater than such a limit n_0 decreases to a minimum value of about 2.5 (Figure 5b). The strain level at which n_0 starts to decrease is equal to about 0.1% even though it depends on soil plasticity and possibly on OCR. More specifically, such a threshold strain level decreases with a decrease in the plasticity index (Figure 5a), in agreement with the concept of volumetric threshold strain and related experimental findings (Vucetic 1994);
- smaller values of n_0 are observed in the case of overconsolidated soils, that is soils with 2<OCR<4 (Figure 5b);
- The variation of n with the number of cycles (*N*), for a given strain level, has been expressed by the following empirical relation (Figure 6a):

$$\log(n) = \log(n_0) - t^* \cdot \log(N) \tag{8}$$

- where the parameter t^* appearing in Eq. 8 describes the decrease of n with the number of loading cycles for a given strain level. Hence t^* represents a sort of degradation parameter and $\delta = n/n_0$ is the degradation index at very small strains, n is independent of N (i.e. t^*=0). Idriss et al. (1978) proposed the degradation parameter t defined by Eq. 9 (Figure 6b):

$$\log(E_N) = \log(E_1) \cdot \log(N)$$

(9)

where E_N is the stiffness at the n^{th} cycle and E_1 is that of the 1^{st} cycle.

The values of *t** and *t* have been compared in Figure 7. A clear correlation exists, and, on average, *t*=1.45 t*.

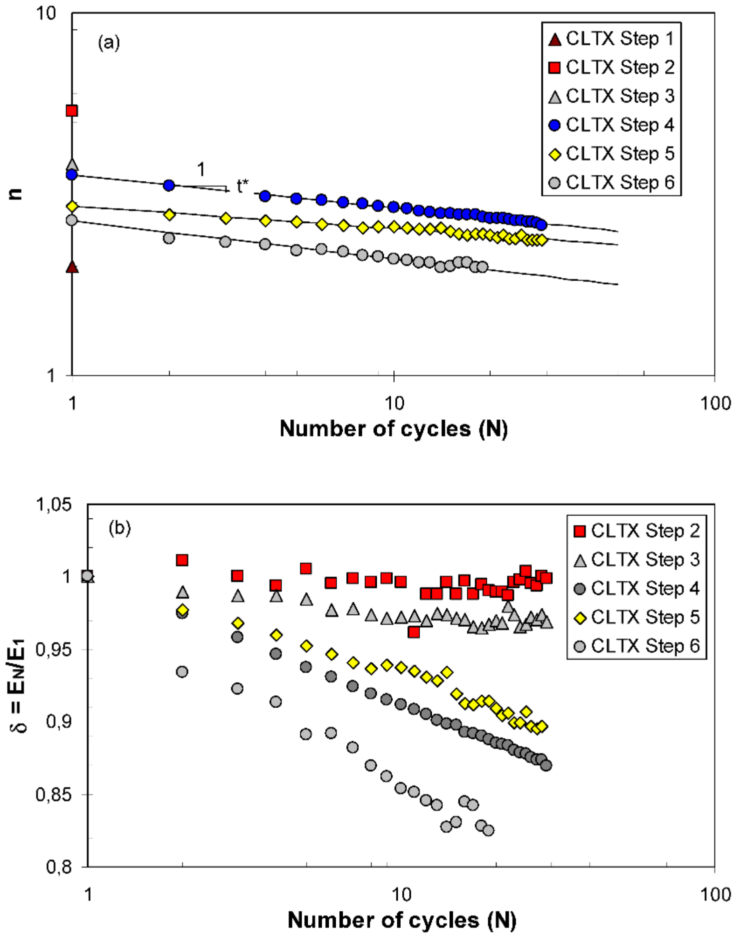

Figure 6 Degradation parameters: a) as defined in this manual; b) according to Idriss et al. (1978)

- The values of t*, obtained from the testing campaign, are summarized in Figure 8. They mainly depend on plasticity index and, for a given soil, on strain level. Therefore, the values of *t** can be obtained from Figure 8, as a function of strain level and plasticity index; in particular for the data of Figure 8, the following empirical relationships have been obtained: 1) $t^* = 0.84\varepsilon_c$ for I_P ranging between 0 and 20%, 2) $t^* = 0.33\varepsilon_c$ for I_P ranging between 20 and 40% 3) $t^* = 0.19\varepsilon_c$ for I_P greater than 40%

- For strain levels greater than those shown in Figure 8, it is possible to use published data on the degradation parameter t (Vucetic and Dobry, 1991), recalling that on average $t^* = 1.45t$.

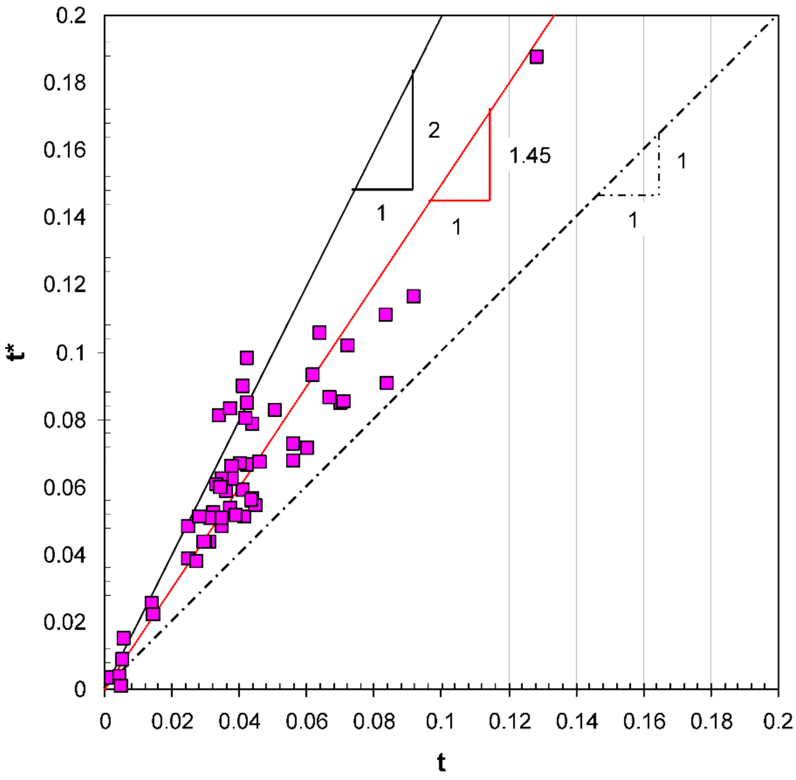

*Figure 7 Comparison between different degradation parameters t and t**

Based on above findings, the calibration of ONDA constitutive parameters has been conducted in this study according to the following criteria which holds for the shear stress:

- shear strain relationship (for the triaxial test results analysed by Rigazio (2001) these criteria have been deduced by assuming the validity of elasticity theory associated with an appropriate value of Poisson ratio):

- For normally consolidated soils it was assumed n_0=5 up to shear strain level of about 0.1%.
- For overconsolidated soils (2 < OCR < 4) it was assumed n_0=3.5 up to shear strain level of about 0.1%.
- For a strain level greater than 0.1 % the decrease of n_0 was assumed according to the curves illustrated in Figure 5b: curve (1) for NC soils and curve (2) for OC soils.
- The values of the parameter t^* were obtained from Figure 8, as a function of strain level and plasticity index ($t^* = 1.26\gamma_c$ for I_P ranging between 0 and 20%; $t^* = 0.49\gamma_c$ for I_P ranging between 20 and 40%, and $t^* = 0.29\gamma_c$ for I_P greater than 40%). For strain levels greater than those reported in Figure 8, were used data on the degradation parameter *t* published in the literature (e.g. Vucetic and Dobry 1991), recalling that $t^* = 1.45t$.

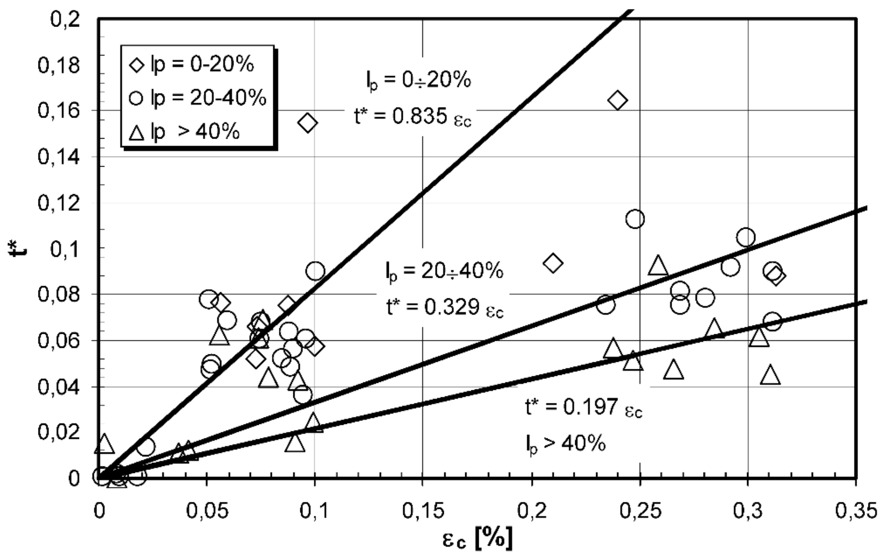

Figure 8 Influence of Ip on degradation parameter

In the case of transient loading the degradation is taken into account in agreement with the suggestions given by Idriss et al. (1978). More specifically:

- changes in δ are evaluated between zero crossing (i.e. for every half cycle);

- degradation index is evaluated by means of the following equation (see Figure 9) $\delta_{BC} = \delta_{AB}\left[1+\frac{1}{2}(\delta_{AB})^{\frac{1}{t^*}}\right]^{-t^*}$, where t^* is the degradation parameter for the strain level γ_{AB}
- both backbone curve and hysteretic curve are degraded; it is assumed that $\delta' = G_N/G_1$ (i.e. the ratio of the secant stiffness at the Nth cycle to that of the first cycle) on the purpose of degrading the backbone curve.

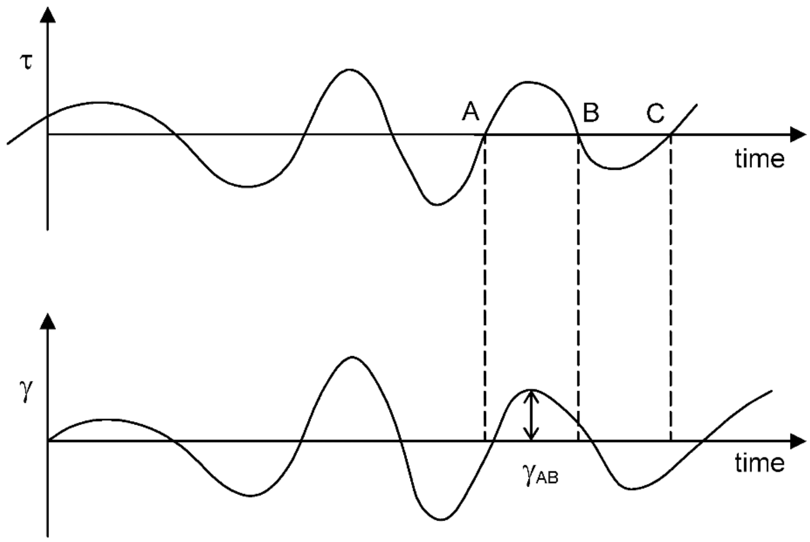

Figure 9 Schematic representation of variations of stress and strain with time

PLEASE NOTE:

In the txt file containing the main properties of the soil deposit:

Thick [m]	Unit W. [kN/m3]	Vs [m/s]	G_0 [MPa]	Damping D_0 [-]	R [-]	alpha [-]	Tau Max [kPa]	OCR (1)	IP [%]	Label [#]
15	19	100	0	0.02	2.05	20.1	0	1	10	1
15	19	400	0	0.02	2.05	20.1	0	2	10	2
0.01	22	1200	0	0.02	0	0	0	2	10	1

Use OCR = 1 if you want to consider n_0=5 (for normally consolidated soils); OCR = 2 if you want to consider n_0=3.5 (for overconsolidated soils); OCR = 0 if you want to use n_0=2.

5.1.2 Convergence parameters

A delicate aspect regarding all discrete models, particularly in non-linear dynamics, is the convergence and stability of the solution in relation to refinement of the discretization scheme. In the Ohsaki's model this is related to the minimum number of sublayers in which to subdivide the macro-layers of the soil deposit. Sub-layering criteria depend on several factors including the number of macro-layers, whether the variation of mechanical impedance with depth is smooth or rough, the frequency content of the seismic excitation. According to Ohsaki (1982) the number of subdivisions N_{sub} is chosen according to the following conditions (the most restrictive): 1) N_{sub} must be such that the periods of vibrations determined by the algorithm are within a 5% error; 2) N_{sub} must be such that the response of the system to a given excitation is computed within a 5% error. Also for ONDA it was adopted the same convergence criterion. Therefore, while macro-strata depend on the geotechnical profile and are defined by the user in the input data file (Matdat), the number of layers in which each macro-stratum is subdivided depends on the above illustrated convergence criteria. The computation accuracy is also affected by the following factors:

- Time interval of the input accelerogram;
- Maximum frequency;

Input accelerogram should be filtered to cut-off frequency higher than 25 Hz. However, no specific procedure is considered in ONDA to filter the input accelerogram.

The time interval of the input accelerogram (*dt*) should be small enough to verify the convergence of the solution. Ohsaki and Sakaguchi (1973) indicate and ideal value of *dt* = 0.625 milliseconds. Such a value is much smaller than the typical sampling time of registered accelerogram (10 ÷ 5 ms). Values of *dt* = 0.0025 to 0.00125s have been usually adopted in ONDA. If the adopted dt is still too small, this involves an arbitrary increase of data points in the original accelerogram.

5.2 Output results

The results of computations are saved as tab delimited txt files in a user-defined folder, using *File → Save ONDA results*.
A list of saved files and their contents and structure is reported in the following:

- ***filename*_profiles.txt** – such a file consists of eight columns:
    - *column 1*: sublayer thickness [m]
    - *column 2*: depth at the middle height of the sublayer [m]
    - *column 3*: vertical effective stress at the middle height of the sublayer [kPa]
    - *column 4*: peak acceleration of the sublayer in [m/s²]
    - *column 5*: maximum shear stress at the middle height of the sublayer [kPa]
    - *column 6*: peak shear strain at the middle height of the sublayer [-]
    - *column 7*: permanent shear strain at the middle height of the sublayer [-]
    - *column 8*: permanent displacement of the sublayer [cm]

- ***filename*_input_acc_spec_depth_acc.txt** - such a file consists of three columns:
    - *column 1:* time [s];
    - *column 2*: the input accelerogram [m/s²];

- *column 3*: the accelerogram [m/s²] at the depth specified by the users in the “ONDA Analysis” Tab at the field “Output-Result Depth”.

- ***filename*_input_acc_fs_spec_depth_acc_fs.txt -** such a file consists of four columns:
  - *column 1:* frequency [Hz] related to the output in column 2;
  - *column 2:* fourier spectrum amplitude of the input accelerogram;
  - *column 3:* frequency [Hz] related to the output in column 4;
  - *column 4:* fourier spectrum amplitude of the accelerogram at the depth specified by the users in the “ONDA Analysis” Tab at the field “Output-Result Depth”.

- ***filename*_ strains_time_hist.txt -** such a file consists of N+1 columns, where the number N is equal to the number of sublayers in which the soil has been discretized by the calculation program:
  - *column 1:* time [s];
  - *column from 2 to N +1*: shear strain time history at the middle height of the sublayer.

- ***filename*_ stresses_time_hist.txt -** such a file consists of N+1 columns:
  - *column 1:* time [s];
  - *column from 2 to N +1*: stress time history at the middle height of the sublayer.

- ***filename*_ accel_time_hist.txt -** such a file consists of N+1 columns:
  - *column 1:* time [s];
  - *column from 2 to N +1*: acceleration time history at the middle height of the sublayer.

- ***filename_* displ_time_hist.txt -** such a file consists of N+1 columns:
    - *column 1:* time [s];
    - *column from 2 to N +1*: displacement time history at the middle height of the sublayer.

- ***filename_* vel_time_hist.txt -** such a file consists of N+1 columns:
    - *column 1:* time [s];
    - *column from 2 to N +1*: velocity time history at the middle height of the sublayer.

- ***filename_* permanent_displ_profile.txt -** such a file consists of 2 columns:
    - *column 1:* permanent displacement at the middle height of each sublayer [m];
    - *column 2*: depth at the middle height of the sublayer [m]

- ***filename_* spec_depth_Elastic_Spectrum.txt -** such a file consists of 2 columns:
    - *column 1:* Period T [sec];
    - *column 2*: Elastic response spectrum PSA [g] at the depth specified by the users in the “ONDA Analysis” Tab at the field “Output-Result Depth”.

Additional results can be computed using the Tab “Other Outputs”. In this Tab it’s possible to calculate and plot: 1) the acceleration time history, 2) the fourier spectrum and 3) the elastic response spectrum for a specified sublayer number. This can be done filling the “Number of the layer” field and pushing the Plot button. Then these outputs can be saved as tab delimited txt files in a user-defined folder, using *File → Save Other results*.

A list of saved files and their contents and structure is reported in the following:

- ***filename*_acc_other.txt -** such a file consists of three columns:
  - *column 1:* time [s];
  - *column 2*: the input accelerogram [m/s²];
  - *column 3*: the accelerogram [m/s²] at the sublayer number specified by the user in the “Other Outputs” Tab.

- ***filename*_ acc_fs_other.txt -** such a file consists of four columns:
  - *column 1:* frequency [Hz] related to the output in column 2;
  - *column 2:* fourier spectrum amplitude of the input accelerogram;
  - *column 3:* frequency [Hz] related to the output in column 4;
  - *column 4:* fourier spectrum amplitude of the accelerogram at the sublayer number specified by the user in the “Other Outputs” Tab.

- ***filename*_Elastic_Spectrum_other.txt -** such a file consists of 2 columns:
  - *column 1:* Period T [sec];
  - *column 2*: Elastic response spectrum PSA [g] at the sublayer number specified by the user in the “Other Outputs” Tab.

The following plots are given:

- **“Accelerogram” Tab**: input accelerogram and that at the depth specified by the users in the “ONDA Analysis” Tab at the field “Output-Result Depth”.
- **“Fourier spectrum” Tab**: Fourier spectra of the input accelerogram and that at the depth specified by the users in the “ONDA Analysis” Tab at the field “Output-Result Depth”;
- **“Elastic R-Spectrum” Tab**: elastic response spectrum of SDOF at the depth specified by the users in the “ONDA Analysis” Tab at the field “Output-Result Depth”;
- shear strain time history at the selected layers;

- **“Strain Displ Time-History” Tab**: Strain and displacement time histories at the selected sublayer;
- **“Peak Profiles” Tab**: maximum acceleration and shear strain profiles;
- **“Stress-Strain” Tab**: stress-strain time histories at the sublayer specified and at the following 3 sublayers;
- **“Permanent displ” Tab**: permanent displacement profile;
- **“Other Outputs” Tab**: acceleration time history, fourier spectrum and elastic response spectrum at the specified sublayer number.

It’s possible to re-load saved results using *View* → *”Load….”* and plot these results using the “Plot ….Viewer” buttons in the plotting Tabs.

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