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NONLIN-EQT: A COMPUTER PROGRAM FOR EARTHQUAKE ENGINEERING EDUCATION

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ABSTRACT

This paper describes a new educational computer program, NONLIN-EQT, which is a consolidation and extensive upgrade of the previous programs NONLIN and EQ-Tools. While many of the features of the original programs have been improved, the most significant improvements are in the ground motion selection, evaluation, and scaling tools, the ground motion attenuation relationship tool, and the structural analysis engine. The program makes extensive use of the PEER NGA ground motion database, and provides a variety of features associated with the related attenuation relationships. The analysis engine has been improved to allow the analysis of more complex systems, and incorporates a variety of inelastic hysteresis models. The engine also provides several new methods for modeling damping in inelastic response history analysis.

Introduction

This paper provides an overview of the new computer program NONLIN-EQT, which is a consolidation and significant upgrade of the previous stand-alone programs NONLIN (Charney 2004) and EQ-Tools (Syed 2004). As with their predecessors, the new program is intended primarily for educational use. However, it is expected that NONLIN-EQT will also find significant use in a variety of professional disciplines related to earthquake engineering.

The original version of EQ-Tools had three primary functions: [1] selection and evaluation of earthquake ground motion records, [2] development and plotting of a variety of ground motion attenuation relationships, and [3] analysis of the influence of site geology on ground motion history. All of these features have been retained in NONLIN-EQT, but only items [1] and [2] have been significantly enhanced. Modifications to item [3] are provided only to preserve compatibility with parts [1] and [2].

The latest independent version on NONLIN had three basic features; [1] selection and evaluation of ground motion records, [2] nonlinear dynamic analysis of simple structural

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systems, and [3] response history analysis and continuous spectral analysis of classically and nonclassically damped elastic multistory shear-frame buildings subjected to simple to harmonic loading. Feature [1] of NONLIN has been merged into the EQ-Tools portion of the combined program. Feature [2] has been enhanced considerably by providing a new Multiple Degree of Freedom (MDOF) analysis engine. However, the simple Single Degree of Freedom (SDOF) model familiar to NONLIN users is still provided. The third feature of NONLIN has been carried over without change into the combined program.

While not particularly relevant to this paper, it is noted that the NONLIN-EQT program has been upgraded from Visual Basic version 6 to Visual Basic.Net version 2008. This upgrade is entirely transparent to the user. The conversion of the program to the 2008 version of VB is expected to provide compatibility with future versions of Microsoft Windows, including Version 7. Most of the graphics in the program are developed using the native graphics functions in VB. A few of the more complex three-dimensional graphs have been developed within the OpenGL toolset.

Organization of NONLIN-EQT

NONLIN-EQT is organized into five modules, as follows:

1. Ground Motion Selection, Analysis, and Scaling Tools
2. Ground Motion Attenuation Relationships
3. Site Analysis Tools
4. Nonlinear Response History Analysis
5. Analysis of Classically and Nonclassically Damped MDOF systems

These modules are, for the most part, independent. However, some information may be passed from one module to the other. For example, firm soil ground motions selected from Module 1 may be converted to soft soil ground motions in Module 3, and then be sent back to Module 1 for evaluation, or used for response history analysis in Module 4. Similarly, response spectra developed from the ground motion attenuation relationships in Module 2 may be used as a basis for scaling of ground motions in Module 1.

The following sections provide a brief overview of the features and principal enhancements in each module.

Module 1: Ground Motion Selection, Analysis, and Scaling Tools

Module 1 provides a variety of tools that may be used to select, analyze, and scale recorded ground motion acceleration data associated with historical earthquakes. The program has a self-contained database of such motions, and currently contains more that 1200 ground motion "sets" from a variety of sources. Each ground motion set consists of two horizontal and one vertical acceleration record.

With regards to ground motions themselves, a significant update from EQ-Tools to NONLIN-EQT is the addition of a Wizard that allows ground motions from the PEER-NGA ground motion database (Chiou, et al. 2008a) to be automatically added to the NONLIN-EQT database. All such motions will be added to the PEER-NGA group, but may also be tagged as a user-defined subgroup. For example, several of the near-field ground motions recommended for use by the ATC-63 project (FEMA, 2009) may be collected and placed into (added into) a separate record subgroup named "ATC-63 Near".

The user may select for analysis one or more ground motion sets from a list, or through the use of a search engine. Search parameters include source (such as PEER-NGA), event (such as Northridge), fault mechanism, magnitude, distance, and site characteristic.

Once the ground motion sets have been selected, there are a variety of evaluation tools available. These tools may operate on an individual set, or on the full group of sets selected. The full list of evaluation tools is too extensive to describe in this paper, so only a few of the newer features are presented below. Most of these new features deal with evaluation of the horizontal components from a given set.

Ground Motion History Plotting
- X-Y plots of acceleration, velocity, or displacement history
- X-Y-X plots of acceleration, velocity, or displacement history
- Horizontal acceleration, velocity, or displacement history at a given compass bearing

Response Spectra Computation and Plotting
- True and Pseudo velocity or acceleration for a given damping value
- Horizontal spectra at a given compass bearing
- Average spectra for horizontal components
- Geomean spectra for horizontal components
- SRSS spectra for horizontal components
- Envelope spectra for horizontal components
- Spectral orbits at given period and damping

Response Spectra Overlays
- Comparison of computed spectra and code spectra
- Comparison of computed spectra with spectra from attenuation relationships

Epsilon Spectra [as defined by Baker and Cornell (2006)]

Where applicable, the above relationships may be plotted for several ground motion sets at once. For example, the envelope spectra for several different ground motions sets may be plotted together, and may be overlayed with code or ground motion model spectra.

NONLIN-EQT provides a number of ground motion scaling tools. The principal scaling tool is based on the scaling requirements provided in ASCE 7-05(ASCE 2005). This scaling tool will also be compatible with the requirements of ASCE 7-10, which are fundamentally similar to those in ASCE 7-05. The ASCE 7-05 scaling methodology for three-dimensional analysis is specified below:

> "For each pair of horizontal ground motion components, a square root of the sum of the squares (SRSS) spectrum shall be constructed by taking the SRSS of the 5 percent-damped response spectra for the scaled components (where an identical scale factor is applied to both components of a pair). Each pair of motions shall be scaled such that for each period between 0.2*T* and 1.5*T,* the average of the SRSS spectra from all horizontal component pairs does not fall below 1.3 times the corresponding ordinate of the design response spectrum, determined in accordance with Section 11.4.5 or 21.2, by more than 10 percent."

In NONLIN-EQT, the ASCE 7 procedure is expanded to allow the scaling to occur over a more general period range αT and βT, and for the factors 1.3 and 10 percent to be modified. For example, setting α=0.2, β=1.5, and resetting the "does not fall below" factor and percentage to 1.0 and 0.0, respectively, produces the scaling procedure adopted in ASCE 7-10. Additionally, the procedure allows the spectrum match over the indicated period range to be a best fit match instead of the more conservative "does not fall below" match. It is noted that the above procedure also allows fundamental period scaling (α and β both set to 1.0) as recommended by Shome, et al. (1998) and the hybrid procedure described by Charney (2010).

An ATC-63 (FEMA 2009) compatible scaling procedure is also provided. The method is best described in the words of ATC-63: "the ground motions are first normalized by peak ground velocity, and are then collectively scaled to a specific ground motion intensity such that the median spectral acceleration of the record set matches the spectral acceleration at the fundamental period *T* of the archetype that is being analyzed".

The as-recorded components of acceleration may be rotated to any orientation (for example, fault-normal, fault parallel) before scaling. Other modification include the ability to scale to code spectra developed for damping values other than 5% critical, to scale to user specified design spectra, or to scale to spectra generated by the attenuation relationships produced in Module 2 of the program.

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Module 2: Attenuation Relationships

NONLIN-EQT includes the attenuation relationships originally included in EQ-Tools, as well as five new relationships that have been developed as a part of the PEER Next Generation Attenuation (NGA) program. Compared to the previous models, the NGA developers have tried to make the new models more realistic by considering a larger database of strong ground motion and using more variables to incorporate complex soil behavior. These models, however, are valid only for shallow crustal earthquakes in active tectonic region whereas the previous version of the program had relationships for subduction zone and stable zone of CEUS. Moreover, previous models have another advantage over NGA models due their ability to predict vertical component of response. Hence, the authors decided to keep the previous models along with the new NGA model in NONLIN-EQT. The new attenuation relationships are as follows:

- Abrahamson, et al., 2008
- Boore, et al., 2008
- Campbell, et. al, 2008
- Chiou, et al., 2008b
- Idriss, 2008)

The regression data tables for each of the relationships are provided as external data files (and are included with the program). Providing the data in this manner makes it easy to update the relationships if the regression data is updated or corrected. After the user enters the appropriate parameters (which vary among the different relationships), a variety of graphs may be produced including:

Spectral acceleration vs distance for a range of magnitudes

Spectral acceleration versus period (Response Spectra) for
a given distance (from source to recording station) and a range of magnitudes
a given magnitude and a range of distances
a given magnitude-distance pair

Where applicable, the plots listed above are developed for a given set of site characteristic (e.g. shear wave velocity). In these cases, the above plots may be formed for a given site type, or for a range of site types.

Spectra that are generated for a specific data set (for example, a given magnitude, distance, and shear wave velocity) may be compared to code spectra or actual ground motion spectra. The spectra may also be used in lieu of the code spectra for the purposes of ground motion scaling.

Module 3: Site Analysis

The site analysis tools that have been implemented in NONLIN-EQT can perform linear and non-linear analyses to predict the response of a one-dimensional layered soil site model. The methodology, algorithms, and FORTRAN subroutines developed for the WAVES program (Hart and Wilson 1989) have been directly implemented into NONLIN-EQT, and in this sense, NONLIN-EQT acts as a graphical pre-and post-processor for WAVES.

For practical considerations, the number of base input ground motions and the number of layers in the soil profile that can be used for site response analysis in the NONLIN-EQT environment have been limited to twelve and ten, respectively. It should be noted that a one-dimensional site model is not applicable for sites with two- or three-dimensional subsurface geometries. But for practical engineering analysis, one-dimensional site models can provide reasonable results that reflect the essential character of site response.

The ground motions searched from the NONLIN-EQT database, and assembled as the suite of motions, form the base input ground motions for analysis with WAVES. Once all the necessary analysis control information, dynamic and geometric properties of soil layers, and the base input ground motion data are available, NONLIN-EQT generates the data files for use with WAVES to perform the site response analysis. The analysis and other necessary processing are performed in the background. Analysis is done progressively for each earthquake in a systematic manner.

As the analysis progresses, NONLIN-EQT imports the layer response acceleration histories by reading the output files generated by waves sequentially. Once the response acceleration histories are available for each layer and each base input ground motion, the computational tools in NONLIN-EQT generate the response velocity and displacement for each layer by integration. The velocity and displacement histories are base-line corrected to establish the zero baselines. The ground motion histories of the layer response can then be graphically compared to the original histories. Also, the Fourier amplitude spectrum and response spectrum can be generated for any base input ground motion and response of any layer of interest and compared graphically. If desired, the site response analysis data can also be stored.

Module 4: Response History Analysis

The response history analysis tool has been expanded to allow the analysis of more general two-dimensional structural systems. Structures may be configured as either a planar frame, or as a planar grid. The planar frame may be used for seismic, wind, and blast load analysis. The grid model is intended for use in the blast-load analysis of window wall systems. A variety of simple systems may be developed through templates. The familiar one-story and one-bay model that has been available since the first version of NONLIN is set up as the default model.

Inelastic behavior is provided by two sets of action-deformation relationships. The first of these relationships, also available in the MDOF models in earlier version of NONLIN, were developed by Sivaselvan and Reinhorn (1999). New to NONLIN-EQT are the "SNAP" models developed by Ibarra et al. (2005). These models provide a variety of degrading strength and degrading stiffness behavior. P-Delta effects are incorporated into the frame model, but have not been implemented into the grid model (as member axial forces are not available in that model).

One of the more interesting features of the new analysis engine is the ability to model damping in a variety of ways. The simplest damping model is mass and stiffness proportional damping. This model may be based on initial stiffness or on the tangent stiffness. The tangent stiffness model provides an option for updating the proportionality constants as the system frequencies change with yielding. The tangent stiffness based models have been shown to control unintended increased in damping as the system frequencies reduce during inelastic response (Charney 2008).

NONLIN-EQT provides a completely new "evolutionary" damping model developed by Bowland, et al. (2010) in which structural damping is added to each element through rotational dampers that are attached to rigid-link ghost elements which are constrained to the structural element (Fig. 1). The deformations along the length structural element are transformed into rotations at the hinges of the rigid-links and into the damping elements.

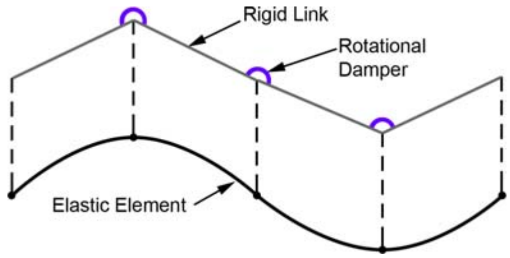

Figure 1. Rigid link model with rotational dampers.

The rotational dampers are modeled with a viscous nonlinear damping model described by Eq. 1.

$$f_d = Csign(\dot{u})|\dot{u}|^{\alpha} \quad (1)$$

where $\dot{u}$ is the rotational velocity in the damper, C is a coefficient of damping, $sign(\dot{u})$ is the signum function that returns -1 or 1, and α describes the shape of the curve. Fig. 2 illustrates different force velocity relationships that are generated by modifying α. The dampers can be modeled as viscous ($\alpha = 1.0$) or may behave similar to Coulomb damping ($\alpha \leq 0.2$). Using this model, the damping character of any structural element can be changed during an analysis by simply modifying the values of C and α. For example, an element may behave like a linear viscous damper during low deformation, or like a Coulomb damper during larger deformations. A variety of simple rules are provided for damper evolution. For example, one rule set uses the accumulated damage index in a member to establish instantaneous damping values.

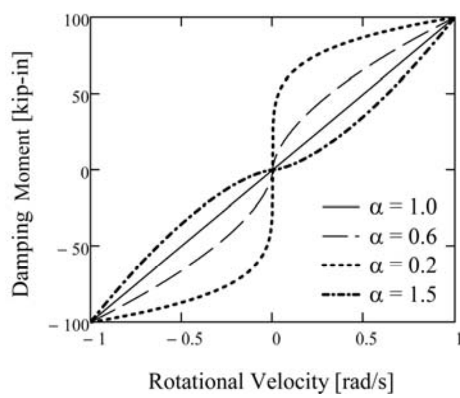

Figure 2. Nonlinear Viscous Damper Constitutive Relationship

Also provided by the program is the ability to easily set up, perform the required analysis, and display the results of an Incremental Dynamic Analysis (Vamvatsikos 2002) of a structural system. In NONLIN-EQT, the IDA may be performed for a variety of ground motion sets which have been automatically scaled to a target spectrum parameter. The user may select a range of ground motion intensity factors and the number of increments of analysis to perform. For example, the analyst may state that the intensity factor shall range from 0.1 to 2.0, in increments of 0.1. A variety of intensity measures may be plotted, including displacement, drift, base shear, energy dissipated, and accumulated damage.

Module 5: Dynamic Response Tools

The fifth module in NONLIN-EQT provides two different "Dynamic Response Tools", one for proportionally damped (classical) systems and one for nonproportionally damped (nonclassical) systems.

The Dynamic Response Tool for Proportionally Damped Systems (DRT-P) was designed to illustrate the concepts of natural mode shapes and natural frequencies. The structural system in the DRT-P is a multi-level linear elastic "shear building". The mass and stiffness is specified for each level, and a damping ratio for each mode is specified. After the properties are entered, the program computes and displays the undamped mode shapes and frequencies. The mode shapes may be animated, showing real time variations in the amplitude of each mode (the animated modes vibrate at "true" frequency).

After the mode shapes are computed, the structure is analyzed for a system of harmonic loads, with the same harmonic loading function applied at each level. The user may specify only the frequency of the harmonic load, but the frequency may be changed at any time during the analysis. The system is analyzed using modal superposition, with each mode's contribution being calculated by the piecewise exact integration method.

If the harmonic load is applied at one of the structure's natural frequencies, the structure will resonate and will eventually begin to vibrate in the mode shape corresponding to the frequency. The vibrating shape of the structure is continuously displayed, together with the response history trace at the top of the structure and a real-time Fourier Amplitude Spectrum of the roof displacement trace. If the loading frequency is changed, say from the first mode frequency to the second mode frequency, the first mode response eventually dies out (due to damping) and the second mode shape eventually emerges as the dominant vibrating shape. Changing to a loading at the third modes' natural frequency, the first mode response reappears due to the introduction of transients, the first and the second mode components of displacement damp out, and the third mode response becomes dominant.

One of the most useful aspects of the DRT is the ability to change the individual modal damping ratios and then to demonstrate the effect. For example, if the first mode damping ratio is increased to 10% and the remaining modes are left at 2%, the first mode response will be seen to decay much more rapidly than when the damping in the first mode was 2% critical.

The Dynamic Response Tool for Nonproportionally Damped Systems (DRT-N) was specifically designed to illustrate the concepts of complex eigenvalues and mode shapes, and to "demystify" these numbers. The DRT-N tool is similar to the DRT-P tool, except that the story damping constants C are explicitly provided, thereby allowing the analysis of nonproportionally damped systems. Once the system properties are input, the eigenvalues and eigenvectors are computed. The eigenvalues are decomposed into to the frequency and damping ratio information they contain, and the eigenvectors are decomposed into amplitude and phase. This decomposition illustrated that complex numbers are really nothing more than a convenient notation, wherein one quantity can store two pieces of information.

Also contained on the tool are animated mode shapes, animated displacement histories for the vibrating shapes, and animated plots of the coordinates of the complex eigenvectors. Animation of the deflected shape for nonproportionally damped systems illustrates the interesting phase relationships that occur in the mode shapes. One good use of the tool is the illustration of the difference between proportionally damped systems (everything in phase) and nonproportionally damped systems (everything mostly out of phase). It may be shown that the higher modes generally contain larger phase differences than the lower modes, and that the more nonproportionally damped a system is, the greater the phase differences.

Future Enhancements

A number of future enhancements are planned for NONLIN-EQT. These enhancements are summarized as follows:

- Generation of artificial ground motions
- Modification of existing ground motions
- Spectrum matching tools
- ATC 63- type quantification of building seismic performance parameters

Conclusions

NONLIN-EQT is an extensive enhancement of the programs NONLIN and EQ-Tools. Previous versions of the program, released separately as NONLIN and EQ-Tools have found use in a number of academic institutions in the U.S., and abroad. It is hoped the newest version will find as broad an acceptance.

The new program (as well as its predecessors) is available free-of charge to faculty and students at academic institutions. The program may also be made available, on case-by-case basis, to persons working outside academia. Persons interested in obtaining a copy of the program should send an e-mail to fcharney@vt.edu. While the program has been tested extensively, it is possible that certain bugs and inconstancies exist, and it is hoped that these will be brought to the attention of the authors. Additionally, any recommendations for improvement of the program will be gratefully accepted.

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