Incorporation of Strong Motion Duration in Incremental-based Seismic Assessments

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Abstract

This study proposes a new approach to incorporate motion duration in incremental dynamic assessments. Whereas it is demonstrated that motion duration can have a noteworthy impact on structural demands, duration has not directly been considered in the dynamic analyses. In the proposed methodology, duration consistent artificial ground motions are generated by adjusting random initial motions so that they get matched to target acceleration spectra and target duration at a given level of intensity measure. In fact, duration consistency is considered in generating artificial motions and hence duration is directly considered in the analysis. Considering the target duration is the novelty of the proposed method. Target duration as well as target acceleration spectra are determined by a simulation approach that is verified by actual data. Lack of enough data for a given site justifies the use of the simulation approach rather than the actual data. However, simulation approaches use attenuation relationships that were developed based on actual data. The proposed duration consistent incremental based seismic assessment is used in nonlinear seismic assessment of two single degree of freedom structures, an SDOF with and one without degrading behavior. It is demonstrated that consideration of duration-consistent ground motions in response history analysis at high seismic levels may lead to an increase of up to 35% of the deformation demands.

Keywords: Incremental Dynamic Analysis, intensity measure, strong ground motion duration, Monte Carlo simulation

1. Introduction

Seismic rehabilitation provisions (e.g. ASCE/SEI 41-17 (2017) and FEMA-356 (2000)) generally present four procedures for seismic analysis: Linear Static Procedure (LSP), Linear Dynamic Procedure (LDP), Nonlinear Static Procedure (NSP), and Nonlinear Dynamic Procedure (NDP). Among these procedures, NDP is utilized to obtain the structural responses under an earthquake ground motion (GM) record, which can consider both nonlinearity of materials and the dynamic nature of earthquakes and is thus taken to be the most exact framework. It is worth mentioning that the NDP is regularly employed for complex structural systems such as based-isolated buildings or structures equipped with the vibration control devices. However, the NDP framework gives the response output for one single level of intensity measure (IM). This means that we can have an analytical result only for one probable seismic scenario. An extension to the NDP procedure is also available in the literature and is called Incremental Dynamic Analysis (IDA) (Vamvatsikos and Cornell 2002). In this framework, structural responses are examined and monitored at different seismic levels instead of one IM level at which the NDP is typically performed. It should be noted that the selected IM has to be actually scalable for the IDA study.

In a single-record IDA, an unscaled (as-recorded) earthquake record is first selected from an official GM database. To track structural responses at multiple levels of excitation, the selected GM is then scaled up and down to cover all desired levels of structural behavior from an elastic status to more plastic ranges, leading eventually to a point recognized as a global collapse capacity of the system (Vamvatsikos and Cornell 2002). Thus, multiple runs of NDP

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have to be executed in this case to cover all the IMs required to see a continuous status of the structural responses under scaled GMs. In this way, the intensity level of the selected record is changed by a simple transformation which can uniformly increase or decrease amplitudes of the motion selected for the single-record IDA study. In other words, a number of scaled images of an accelerogram with different intensity levels are imaginary produced from the original (as-recorded) accelerogram (Vamvatsikos and Cornell 2002; Mackie and Stojadinovic 2005). Any desirable damage measure (DM) can be hired to record the structural responses through multiple levels of IM. The DMs computed at different levels of IM are normally plotted against the respective level of IMs employed. And, therefore, one continuous response curve—known as the single IDA curve—is obtained in this way. For performing a multi-record IDA study, a set of GMs should be selected in advance for the entire IDA procedure. In this way, the dispersion of the responses at a given level of IM is no longer of deterministic type and can be represented using random function conditioned on an IM level, \( DM = f(IM) \) (Vamvatsikos and Cornell 2002).

While it is worth to be mentioned that the IDA framework is now being considered as the most reliable computational tool for estimation of seismic demands of structures, researchers are trying to offer some ways to make this framework become less computationally demanding or sound more realistic. In this case, a few modifications to the procedure of an IDA framework are normally suggested in such studies. Since the fact that an IDA study needs numerous NDP analyses at multiple seismic levels from various selected GMs, it can be understood that it demands massive computational efforts. In this case, to reduce or obviate the computational demands of an IDA study, one may decide to utilize the recommended equivalent SDOF systems (Vamvatsikos and Cornell 2005) or use a type of pushover analyses on the detailed 3-D MDOF models to predict the IDA responses (Han and Chopra 2006; Soleimani et al. 2018). Furthermore, some researchers (Hedayat et al. 2019; Manafpour and Jalilkhani 2019; Peruṣ et al. 2012) also derived empirical formulas by which summarized IDA curves can be determined by an acceptable approximation. In order to avoid the complexities associated with the record selection procedure of an IDA study (Araújo et al. 2016; Baker and Cornell 2006), Azarbakht and Dolšek (2007) proposed a record selection procedure by which a reduced number of selected GMs would be required for a reliable estimation of median IDA response. A reduced number of GMs can be also found in the ET method by which summarized IDA response curves can be readily computed using three NDPs only (Mashayekhi et al. 2019). In the ET method, structures are exposed to three different intensifying GMs that are simulated in a way that the IM level in a GM increases by the time. Instead of using a record set for the entire analysis in the IDA, Lin and Baker (2013) proposed a new IDA procedure—named Adaptive Incremental Dynamic Analysis (AIDA)—in which a new record selection should be done at each level of IM. They state that the framework AIDA is more consistent with the concept of GM deaggregation in the Probabilistic Seismic Hazard Analysis (PSHA). In this way, target distributions of the significant characteristics of the employed GMs at each level of IM change once the level of IM in the AIDA gets altered.

Even though several studies indicate that duration of the earthquakes may have a significant influence on the structural responses, the duration of motions is not yet being considered for the record selection procedure of current frameworks for dynamic analysis or in a standard IDA study. It was reported that seismic responses of the structures under earthquake loadings with deteriorative behaviors, including RC frames (Belejo et al. 2017, Chandramohan et al. 2016, Han et al. 2017, Hancock and Bommer 2007, Raghunandan and Liel 2013), concrete dams (Sherong et al. 2013, Wang et al. 2015, Bin Xua et al. 2018, Wang et al. 2018) and masonry buildings (Bommer et al. 2004), are much more sensitive to the duration of the ground motions. It means that more damages would be expected to occur in the structures that are subjected to long-duration ground shakings (Harati et al. 2019). In this case, accumulated damage indices which are based on hysteretic cyclic energy of the earthquakes such as Pak-Ang damage index are demonstrated to have high correlations with motion durations. Besides, the extreme damage indices such as peak floor drifts or peak plastic rotations of the elements are also susceptible to this parameter (Hancock and Bommer 2007, Sarieddine and Lin 2013, Mashayekhi et al. 2019). Moreover, it should be noted that the same results apply for the steel (Bravo-Haro and Elghazouli 2018, Hammad and Moustafa (2019, 2020)) and wood frame (Pan et al. 2018) structures.

A methodology is proposed in this paper to incorporate duration influence on the structural earthquake demands, thereby trying to offer a more accurate and duration-dependent analytical framework for incremental-based dynamic analyses. In this framework, artificial duration consistent ground motions are generated by modifying initial motions in such that they get fitted to the target acceleration spectra and target duration. These targets are produced through a simulation procedure for all IM levels required for the proposed duration consistent dynamic analyses. Like any other simulation schemes used in the seismic hazard assessment, the simulation process utilized in this study works
based on the attenuation relationships which are themselves according to the real data. To show the efficiency of the proposed method, numerical examples associated with the validation of the simulation method and application of the proposed methodology in the nonlinear dynamic assessment are thoroughly presented and discussed. To finish, a discussion along with a conclusion section is provided to deliver the main findings of this investigation.

2. Methodology

In the conventional incremental dynamic analysis, various levels of IM are produced by scaling up and down of a set of GM suite. In the IDA, as mentioned before, this scaling procedure is utilized as a mechanism to change the level of IM at which dynamic time-history analysis should be performed for a set of GMs. However, this scaling process leads to the same spectral shape and duration for each individual earthquake record—which is existed within the suite of GMs—at different seismic levels considered. On the contrary, levels of IM are not considered to be increased with the GM record scaling in the proposed framework; intensity level would be intensified with a devised mechanism in this recommended dynamic procedure while both the spectral shape and motion duration of the employed earthquake records get changed for all selected or required levels of IM. In other words, the proposed method are developed to incorporate the variation of spectral shape and motion duration with respect to the chosen level of IM on which dynamic time-history analysis procedures should be executed. The methodology is presented in a stepwise manner as follow:

- Select an appropriate intensity measure (or IM), e.g. peak ground acceleration, peak ground velocity or acceleration spectra at first mode period. Afterwards, assign a required range for the IM you need to have for an IDA procedure and then discretize the considered IM over this range at $N_{IM}$ points. The arithmetic discretization of IM levels is shown through Equation (1)

$$ IM_i = IM_{\min} + i \times \frac{(IM_{\max} - IM_{\min})}{N_{IM}} $$

where $IM_{\min}$ and $IM_{\max}$ are, respectively, the minimum and maximum considered IM values; $N_{IM}$ is the number of discretization points, and $IM_i$ is the i-th level of IM in the aforementioned range of IMs.

- Develop relationship functions for spectral acceleration and motion duration as a function of IM level. These relationship functions are obtained using the data of the events provided through a simulation process. Comprehensive explanations for derivation of such these relationship functions are brought under section 4. General forms of these functions can be written as:

$$ dur = f_{Dur}(IM) $$
$$ S_a = g_{Spec}(T, IM) $$

where the functions $f$ (IM) and $g$ (T, IM) are random lines (functions), which are generated to show the variability of motion duration and spectral shape of a set of hypothesized GMs considered for a given level of IM in the proposed dynamic procedure.

- Simulate $N_{GM}$ artificial motions at each IM level based on the information derived in previous step. Accordingly, $N_{GM} \times N_{IM}$ artificial motions would be produced at this stage as it is indicated in Equation (4):

$$ GM_{i,j} = GM(IM_{i}, S_a = g_{Spec}(T, IM_{i}), dur = f_{Dur}(IM_{i}), X_j) $$

where $j$ is an index representing the required number of GMs that should be simulated at each level of intensity measure, the $IM_i$ in Equation (4). And $X_i$ is the initial motion used to simulate j-th ground motions, where this initial motion is randomly simulated for this step of the analysis.
• Perform nonlinear time-history dynamic analysis of the structure under all simulated artificial motions. All critical response parameters should be recorded during time history analysis.

• Evaluate engineering demand parameter (EDP) of the structure for each dynamic analysis. One possible engineering demand parameter is maximum inter-story drift ratio. One can also choose damage parameters such as Park-Ang metric (Park et al. 1987) for the demand parameter. The matrix of EDP as presented in Equation (5) is the output of this step.

\[
EDP_{ij} = \left[ EDP \left( GM_{ij} \right) \right]
\]

• Plot each individual pairs of IM versus EDP values \((IM_{i}, EDP_{j})\) to show the scattering trend of the results.

• Calculate the median and the standard deviation of EDP values at each level of IM. These central values of EDP—for example, the medians or means as brought in Equation (6)—should be determined for all considered levels of IM. Plot pairs of central EDP values against the discretized IMs \((IM_{i}, EDP_{j})\) to obtain a duration-dependent response curve of a structure.

\[
EDP_{ij} = \frac{\sum_{j=1}^{N_{GM}} EDP_{ij}}{N_{GM}}
\]

3. Relationship between motion duration and intensity measures

3.1. Proposed simulation procedure

In this section, a procedure for determining the relationship function between a candidate IM and motion duration is explained for a specific site. The resulting relationship functions, as mentioned in section 3, are used in the method developed in this study—the duration-consistent incremental dynamic analysis. For establishing such a relationship function, Monte Carlo Simulation (MCS) is employed to be at work for the data sampling that is explained below. MCS is a powerful statistical analysis method that is widely applied to many problems existing in different fields to perform numerous experiments on the computer. It is also being employed frequently in the seismic risk assessment as well (e.g. Bourne et al. 2015, Bommer et al. 2017). MCS can be used in complex and highly nonlinear engineering models because it can deal with a lot of random variables with different distribution types. For each experiment, a set of input random variables \(X = (X_1, X_2, \ldots, X_n)\) is sampled or generated. Then the output variable or the performance function \(Y = g(X)\) is computed using the input data of all rounds of the experiment. The following three steps should be performed for reaching out a relationship function between motion duration and the IM selected to be employed for proposed dynamic analysis:

i. First we should find characteristics of the earthquakes that can all produce a specific level IM. For this purpose, we have to use attenuation relationship function or ground motion prediction equations (GMPEs). These relationships are typically dependent on a number of contributing elements which include parameters pertinent to the site, source and variables standing for the distance-related regressors. In this regard, an appropriate GMPE should be selected for converting the chosen IMs—as it is discretized in section 2—to the characteristics of the expected earthquake events. This attenuation relationship is indeed required for use in an inverse problem-solving procedure, which is in contrast to the conventional application of such equations. In this study, the GMPE of Boore et al. (2014) developed to predict the amplitude-based IM of the earthquake events for a specific site has been selected for the above-mentioned inverse problem-solving. In this case, all contributing factors of this GMPE, except for the moment magnitude M, are chosen based on the characteristics of the scenario earthquakes expected at a specific site of interest. These factors, which are fully explained under section 3.2, are then employed for use in Equation (7) to solve for a corresponding value of M that will be used instead of the selected IM in the next step.
\[
\ln Y = F_E(\mathbf{M, mech}) + F_p(R_{JB, \mathbf{M, region}}) + F_S(V_{s30, R_{JB, \mathbf{M, region}}, z_1}) + \varepsilon_n \sigma(\mathbf{M, R_{JB, V_{s30}}})
\]  

(7)

where \(\ln Y\) is the natural log of an amplitude-based intensity measure such as PGA, PGV or 5% damped PSA; \(F_E\) and \(F_p\) are functions related to the source- and path-term parameters (“events”); \(F_S\) is a function for site term. \(\varepsilon_n\) is an error term, and \(\sigma\) is a function representing the total standard deviation of the model. For further information regarding a detailed explanation about the functions reflected in the prediction model of Equation (7), readers can consult Boore et al. (2014). The independent variables of each function, such as \(V_{s30}\) and \(R_{JB}\), used in Equation (7) are adequately explained and discussed under section 3.2.

ii. The motion duration of the scenario earthquakes is subsequently generated for each level of IM, where an MCS-based simulation process would be employed in this proposed framework. In this regard, a compatible GMPE should be considered and selected for motion duration of the earthquake events whose characteristics—including the moment magnitude \(M\)—have been nominated from the previous step. Since significant duration for 5-75% of normalized Arias Intensity has been decided to be hired as a metric for motion duration quantification, the attenuation relationship function developed by Afshari and Stewart (2016) is employed for the MCS-based data sampling of this study. As reflected in Equation (8), the standard error term \((\varepsilon_n)\) of this GMPE is considered as a random variable for this data sampling simulation. It is worth mentioning that the GMPE derived by Afshari and Stewart (2016) is quite compatible with the one chosen in the previous step because both of them have been derived from the same identical number of events and database—namely the NGA-West2—and had the same screening protocol as well.

\[
\ln D = \ln(F_{Ed}(\mathbf{M, mech}) + F_{pd}(R_{rup})) + F_{sd}(V_{s30, \delta z_1}) + \varepsilon_n\sigma_d(\mathbf{M})
\]  

(8)

where \(\ln D\) is the natural log of significant duration; \(F_{Ed}\) and \(F_{pd}\) are functions derived to stand for the source- and path-term parameters; \(F_{sd}\) is also a function to represent site term; \(\sigma_d\) is a function for the total standard deviation of the significant duration model. For additional explanations about the functions reflected in the prediction model of Equation (8), readers are invited to see Afshari and Stewart (2016). The independent variables of each function, which is used in Equation (8), are sufficiently described in section 3.2.

iii. The median duration value of the simulated events at each IM level is individually determined. Next, a relationship function, i.e., \(dur = f_{dur}(IM)\), is obtained using a moving average or a least-square optimization method. The former fitting method has been employed in this research.

The flowchart for the aforementioned simulation process is provided in Figure 1 where the term “mech” denotes fault type mechanism, and the term named “dIM” is standing for each increment of IMs being employed in the proposed method. As can be seen from Figure 1, the site and fault parameters of a scenario earthquake should be specified before the simulation procedure. These parameters, controlling the data sampling of a specific site, are fully described in section 3.2.
As can be readily understood from the simulation algorithm displayed in Figure 1, thousands of possible earthquake scenarios are simulated by the proposed data sampling, which seems to be in contrast to the use of real GMs which are limited to a finite number of motions recorded from previous events. Hence, a potential advantage of using simulated data is that it might be possible to seek the relationship of a duration-related parameter and an amplitude-based IM with adequate amounts of data, especially for the higher levels of IM. Nevertheless, to check the authenticity and robustness of the proposed MCS-based simulation, characteristics of four real earthquake records have been randomly selected from the NGA-West2 in this regard. These earthquake records are represented by their
Record Sequence Number (RSN) in the NGA-West2 database. For example, a ground motion with RSN of 200 is one of the records remained after the Imperial Valley earthquake of 1979. In this case, the real characteristics of these GMs are first chosen as the inputs for step 2 of this proposed simulation procedure. Then, thousands of motion duration are simulated using the input characteristics of each GM record. Next, a normalized probability density function is obtained based on the simulated data provided by the characteristics of each earthquake event considered. As can be seen in Figure 2 (a) to (b), the median value of the simulated motion duration samples can well estimate the values representing the real motion duration for each GM.

Figure 2. Simulated samples of motion duration versus the values representing the corresponding quantities for real ground motions: a) Tottori earthquake of 2000; b) Imperial valley earthquake of 1986; c) Chuetsu earthquake of 2007; d) Pakistan earthquake of 2005

3.2. Parameters of the scenario earthquake

In order to determine a relationship function between motion duration and a candidate IM, variables pertinent to the simulation process of a given site should be first identified. In this case, soil condition parameter is expressed by means of the time-averaged shear wave velocity over a sub-surface depth 30 meters, \( V_{s30} \). Even though ambient experiments are needed to determine this parameter value for a site, this study simply uses the recommendations provided by NEHRP provisions (1997). Depth parameters \( Z_{1.0} \) and \( Z_{2.5} \) are defined as the depth level at which shear wave velocity reach 1000 m/s and 2500 m/s, respectively. The \( Z_{1.0} \) depends on the \( V_{s30} \) and is calculated according to a relationship developed by Abrahamson and Silva (2008) as expressed by Equation (9). The \( Z_{2.5} \) is then computed by an extrapolation procedure based on \( Z_{1.0} \) parameter as recommended by Campbell and Bozorgnia (2006).
Multitude distance measures are recommended to describe the distance-related parameters, including the rupture and Joyner-Boore distance. The rupture distance ($R_{rup}$)—which is defined as the slant distance to the closest point on the rupture plane—is employed to be as a constant variable hereafter because there is regularly a constant distance between the faulting point and where ground motions are recorded. In this case, while earthquakes are always originated from a single seismic source, several different distances (i.e., 10, 15 and 20 km) from an active fault have been chosen for this investigation. This can cover a range of distances from near-source events to the ones related to the far-sources. In addition to rupture distance, existing attenuation relationships may also need the Joyner-Boore distance ($R_{JB}$) which is defined as horizontal distance to the surface projection of the rupture. This distance ($R_{JB}$), as shown in Figure 3, is independent of the rupture distance in general, but in this study the Joyner-Boore distance is assumed to be equal to the rupture distance.

In Figure 3, $\delta$ is fault dip, $W$ is down-dip rupture width, and $Z_{TOR}$ is depth-to-top of the rupture. Dip is the angle that a planar geologic surface is inclined from the horizontal one, where strike-slip faults are assumed to be vertical ($\delta=90$). Moreover, the average values of dip angle equal to 50 and 40 are recommended for normal and reverse faulting events, respectively (Kaklamanos et al. 2011). $R_X$ is the horizontal distance to the surface projection of the top edge of the rupture, which is measured perpendicular to the fault strike and is computed by Equation (10):

$$Z_{1.0} = \begin{cases} 
\exp(6.745) & V_{S30} < 180 \text{m/s} \\
\exp\left[6.745 - 1.35 \ln\left(\frac{V_{S30}}{180}\right)\right] & 180 \leq V_{S30} \leq 500 \text{m/s} \\
\exp\left[5.394 - 4.48 \ln\left(\frac{V_{S30}}{500}\right)\right] & V_{S30} > 500 \text{m/s}
\end{cases}$$ (9)
where $\alpha$ is the source to site azimuth that for a given site is the angle between the positive fault strike direction and the line connecting the site to the closest point on the surface projection of the tope edge of the rupture (Chiou 2005). This angle is assumed positive when it is measured clockwise as shown in Figure 4.

**Figure 4. Plan view of a fault rupture (Kaklamanos et al. 2011)**

For computing the distance-related parameter $R_x$ from Equation (10), the relationship developed by Wells and Coppersmith (1994) is used to estimate the down-dip rupture width ($W$) from moment magnitude and the style of faulting as brought in Equation (11). It is worthy to add that different fault types can be considered for simulation procedure, namely the normal, reverse and strike-slip.

$$W = \begin{cases} 10^{0.76+0.27M} & \text{for strike-slip events} \\ 10^{1.61+0.41M} & \text{for reverse events} \\ 10^{1.14+0.35M} & \text{for normal events} \end{cases}$$
As can be readily understood, a term standing for the depth-to-top-of-rupture \( Z_{TOR} \) should be determined as an input variable of Equation (10). The method employed by Kaklamanos et al. (1994) is also used to estimate \( Z_{TOR} \) from hypocentral depth \( Z_{HYP} \), down-dip rupture width \( W \), and dip angle \( \delta \) as expressed in Equation (12):

\[
Z_{TOR} = \max\left[ (Z_{HYP} - 0.6W \sin \delta), 0 \right]
\]  \hspace{1cm} (12)

where \( Z_{HYP} \) is hypocentral dept, which can be determined according to Equation (14):

\[
Z_{HYP} = \begin{cases} 5.63 + 0.68M & \text{for strike-slip faulting} \\ 11.24 - 0.2M & \text{for non-strike slip faulting} \\ 7.08 + 0.61M & \text{for general (un specified) faulting} \end{cases}
\]  \hspace{1cm} (13)

### 3.3. Relationship functions between duration and PGA

In this section, for a selected site with the parameters described below, the proposed approach is employed for developing the relationship function between peak ground acceleration (PGA) and the significant duration of 5-75% normalized Arias-Intensity.

- \( V_{s30} = 400 \text{m/s} \)
- Fault type= Reverse
- \( R_{rup} = 15 \text{Km} \)

Simulation number of 5000 is used for this site. PGA is used as intensity measure and is explored in the interval of \([0.001g-0.4g]\) with an increment equal to 0.001g. Thus, 1,955,000 simulations are carried out to derive the relationship function for this site. Raw data points generated through this simulation procedure are depicted in Figure 5. While insufficient data for large earthquake events can make computational problems for statistical analyses—especially for higher IM levels—to assess a significant characteristic of the scenario earthquake, simulation procedure is performed to such an extent that the number of events at different IM levels is nearly the same (Musson 2000). This is because the confidence interval length has an inverse relation with the number of samples, so providing an equal number of events for all possible intensity measures is the potential advantage of this method. As can be seen, scattering of the raw data points is clearly pronounced; however, increasing trend of the simulated events is apparently recognizable. It is of noteworthy to mention that the observed scattering is mainly due to the dispersion of the data obtained by the selected attenuation relationship.

![Figure 5. Raw simulated data results for a site of interest (1,955,000 data points)](image-url)
An exponential function form as brought in Equation (14) is fitted to the generated data. This fitted function along with the median of the generated data points are shown in Figure 6. In Equation (14), a, b, c, and d are constant parameters which can be readily determined by any least-square optimization approach. In this study, lsqnonlin command of the software Matlab (2018a) is hired to determine the fitted function.

\[ f(PGA) = a + b \cdot e^{c(PGA-d)} \]  

(14)

The influence of different factors on the relationship function between intensity measure and motion duration is also investigated. In this case, the rupture distance, fault-type, and soil condition are considered for this sensitivity analysis. Figure 7 compares the influence of different rupture distances on the relationship functions derived for a specific site. This figure, which considers three rupture distances, i.e. a 10Km, 15Km, and 25Km, shows that the more rupture distance is selected, the more variation is seen for the duration parameter in the relationship functions. As can be seen from Figure 7, larger values for the motion duration at a given level of IM are predicted by the simulation procedure whenever farther source-to-site distances are selected to be employed in this case. An exponential function can be fitted to the data points derived for each distinct simulation—cases with 10, 15 and 25 Km as shown in Figure 7. As it is readily evident, a region with a steady growth rate can be also found at the beginning of each curve.
Figure 7. The relationship functions between motion duration and PGA as an IM for three different rupture distances.

Figure 8 compares the effect of faulting mechanism on the derived functions, where three fault types—including a reverse, a strike-slip, and a normal fault—are considered for this sensitivity analysis. Note that these functions are obtained for a site with $V_{s30}=400$ m/s and $R_{rup}$ of 15Km. It is of the essence to note that while the normal fault produces a larger range of earthquake durations, the strike-slip fault delivers a lower range of duration values. However, the faulting mechanism can have a minor impact on the regions of the relationship functions at which a steady growth rate is developed—the zone which is located at the beginning of the curves. Therefore, it is clearly discernible that the motion duration of the simulated events at the higher IM levels shows a heightened sensitivity to the faulting mechanism.

Figure 9 compares the influence of $V_{s30}$ value on the derived relationship function, where three types of $V_{s30}$ are considered—namely 400m/s, 600m/s, and 1000m/s. This figure reveals that the motion duration of the earthquake events are more sensitive to the $V_{s30}$ of the sites located in stiffer soils. In general, the median predicted values associated with motion duration are much higher in case the events are simulated for the sites with smaller values of $V_{s30}$. 

Figure 8. The relationship function between duration and PGA for three different fault type for a site with $R_{rup}=15$Km and $V_{s30}=400$ m/s

Figure 9 compares the influence of $V_{s30}$ value on the derived relationship function, where three types of $V_{s30}$ are considered—namely 400m/s, 600m/s, and 1000m/s. This figure reveals that the motion duration of the earthquake events are more sensitive to the $V_{s30}$ of the sites located in stiffer soils. In general, the median predicted values associated with motion duration are much higher in case the events are simulated for the sites with smaller values of $V_{s30}$. 

Figure 9.
As it is quite obvious, a section with a steady growth rate can be also found at the onset of these fitted exponential functions of PGA against D5-75, which gets a bit expanded in case smaller $V_{S30}$ parameters are taken to be applied.

![Graph showing the relationship between PGA and D5-75 for three different $V_{S30}$ for a site with $R_{rup}=15$Km and reverse fault type](image)

Figure 9. The relationship function between PGA and D5-75 for three different $V_{S30}$ for a site with $R_{rup}=15$Km and reverse fault type

4. Application of the proposed method in nonlinear seismic assessments: A case study

4.1. Duration-consistent response spectra as a function of intensity measure

For performing a duration-consistent IDA procedure, we need to have a set of duration-consistent GMs for each IM level considered. But we also need a number of duration-consistent response spectra for each level of considered IM before we go ahead with the simulation of the aforementioned duration-consistent GMs. To clarify this matter, an example is taken for a specific scenario earthquake. For each simulated scenario earthquake with $R_{rup}=20$ km, $V_{S30}= 400$ m/s and Reverse fault type, first an acceleration response spectrum and its related duration parameter are generated. Based on the proposed method of this paper, the median values of the spectral acceleration and motion duration are then computed for the simulated data of each sample. In order to produce duration-consistent GMs, the median acceleration spectrum is generated at 64 levels of IM or in 64 different samples, where each spectrum is associated with a median $D_{h-75}$ parameter. In other words, these motions—which can then be used for the application of nonlinear seismic assessment—are based on the median response spectra that are produced in 64 levels of SA. Four of these simulated spectra, with their IM levels and associated duration parameters ($D_{5-75}$), are displayed in Figure 10. As can be seen from this figure, each spectrum with a specific IM level is accompanied by a unique $D_{5-75}$ parameter both of which are found according to the proposed simulation method. Besides, it is evident to see that spectral shape at each level of IM gets dynamically altered in this proposed framework.
Figure 10. Generated median response spectra with different IMs and D5-75 parameters

4.2. Duration-consistent ground motions

Based on the duration-consistent response spectra that are normally generated in previous step or in section 4.1, duration-consistent GMs should be produced using techniques available in the literature to generate a set of spectrum-compatible artificial GMs. In this study, a set of GMs is simulated for each IM level employing duration-consistent response spectra of the scenario earthquake computed in section 4.1. Using SeismoArtif (2018) software, a bin of 8 ground motions is generated based on each median spectrum acceleration as well as the associated median D\_5\text{−}75 parameter, where each artificial ground motion is simulated utilizing power spectral density function of Gasparini and Vanmarcke (1976) and the shape function of Saragoni and Hart (1973) as envelope shapes. The response spectra pertinent to a bin of generated motions, with a target spectrum created based on IM=0.382g and D\_5\text{−}75=8.3\text{sec}, are plotted in Figure 11.

Figure 11. Response spectra of the duration consistent records along with the their target spectrum for IM=0.382g and D5-75=8.3sec
Note that duration parameter \(D_{5-75}\) is generally increased as the SA is increased up to the level of 64. Therefore, 512 duration-consistent GMs are produced, which are subsequently used for the nonlinear seismic assessment. Simulated GMs at four intensity levels, with IMs equal to 0.154g up to 0.588g, are presented in Figure 12 (a) to (d).

![Graphs showing simulated earthquakes with different IMs and motion durations: a) IM=0.154g, D5-75=5.1sec; b) IM=0.221g, D5-75=6.4sec; c) IM=0.382g, D5-75=8.3sec; d) IM=0.588g, D5-75=14.2sec](image)

Figure 12. Simulated earthquakes with different IMs and motion durations: a) IM=0.154g, D5-75=5.1sec; b) IM=0.221g, D5-75=6.4sec; c) IM=0.382g, D5-75=8.3sec; d) IM=0.588g, D5-75=14.2sec

4.3. Nonlinear seismic assessments of case study models

Two SDOF systems, one with degrading behavior and the other one without degradation, are taken to investigate the application of the proposed method in the nonlinear seismic analysis. In this case, structural SDOF systems with a 1-sec period of vibration are considered to be exposed to a set of duration-consistent GMs generated for the scenario earthquake of section 4.2. The inelastic SDOF systems with degrading and non-degrading behavior are modeled using bilinear and Ibarra-Krawinkler hysteretic model (Ibarra et al. 2005), respectively. The employed hysteretic
models for both degrading and non-degrading SDOF systems are displayed in Figure 13. For both degrading and non-degrading models, \( F_y/W \) is set to be 0.082, where \( W \) is the weight of SDOF systems and \( F_y \) stands for the yield strength. Factors associated with the hardening as well as post-capping stiffness, \( \alpha_h \) and \( \alpha_c \), are selected to be 0.006 and -0.02, respectively. Residual strength is also 0.01 of the yield strength (\( \lambda = 0.01 \)).

![Diagram](image)

Figure 13. Employed hysteretic models: a) bilinear elastoplastic model utilized for non-degrading SDOF system; b) backbone curve of the Ibarra-Krawinkler used for degrading SDOF system (Ibarra et al. 2005)

The median response curves to predict the seismic behavior of the systems are obtained by two different approaches. First, a procedure similar to the cloud analysis is done considering all duration compatible ground motions (Mackie and Stojadinovic 2005). This means that the number of nonlinear time history analysis, required at each seismic intensity level, is performed using a bin of ground motions that are compatible with the considered seismic intensity level. In this case, the median response curve is obtained by computing the average of the median value of responses at each level of SA. An standard IDA procedure, which is completely similar to the classical IDA analysis, is also considered afterward. In this case, just one set of ground motions is selected and then scaled for all intensity levels. For this purpose, a bin of ground motions generated for the thirtieth level of SA (with IM=0.382g) is selected as the record set for the IDA procedure. Therefore, scaling down and up procedures should be followed for computing the median response curve in this IDA framework.

Figure 14 demonstrates the median response curves for the two above-mentioned seismic response procedures (i.e., the IDA and cloud-like response procedures). These response curves are obtained using two inelastic SDOF systems, with and without degradation capturing capability. Mean ductility factors, \( \mu = \delta_{\text{max}} / \delta_y \), at several levels of seismic intensity are also provided for each mean response curve, where \( \delta_{\text{max}} \) is the absolute value of displacement response a system may experience in an earthquake and \( \delta_y \) stands for the yield displacement of the system. As can be seen from this figure, the median response curves are generally in a good agreement for all levels of SA up to the 0.35g while they get widely separated from each other at the higher levels of seismic intensity. It is apparently recognizable that the median response curves computed with cloud-like dynamic analysis, for both models with and without degradation, demonstrate softening initiation around the SA level equal to 0.4g. But the median response curves of the IDA analysis—which is performed with the GM records of IM=0.382g—do not show the aforementioned softening initiation points in such an extent. Besides, the proposed method shows relatively higher ductility factors compared to the standard IDA procedure at the upper levels of seismic intensity, which demonstrates that considered structural systems in this analytical framework have experienced further nonlinearity. As it is expected and seen in Figure 14, higher values of ductility factor bring more scattering in the computed displacement responses. All in all, it can be understood that the differences witnessed in the median response curves for the higher level of seismic intensity are due to the fact that the duration effect of the ground motions is not suitably incorporated in the standard IDA procedure. The reason may be due to the fact that just the amplitude-based
intensity measure (here SA) is scaled in the such IDA procedure while both the level of SA and the related duration of motions are simultaneously changed in the proposed cloud-like response procedure through which a different bin of duration-consistent GMs is taken at each seismic intensity level.

![Diagram](image)

**Figure 14.** Median response curves and the associated data related to the response of each individual ground motion: a) for a non-degrading SDOF model with T1=1 sec; b) for a SDOF model with degradation and T1=1 sec
5. Discussion

In the IDA framework, the levels associated with IM are changed by scaling up and down of a set of GMs selected before the analysis. In this case, IMs are monotonically increased from a low level of excitation up to where recognized as a seismic level believed to cause a collapsing mechanism for the structure of interest. In this way, the spectral shapes as well as the duration of the selected records are kept constant during the process of record scaling. Therefore, the variability of responses at a given level of IM in IDA framework is mainly due to two matters: the first one is the concept known as the record-to-record variability and the next one is related to the level of IM at which responses are obtained. Record-to-record variability can include the dispersion of the structural responses for different applied GMs. As a result, we may have different structural responses when our structure is subjected to different ground motion records. Besides, the range of this response variability may get changed (or widened) when the intensity level of the applied GMs is changed (or increased) for different considered levels of IM. As a result, the dispersion of the damage measure given an IM can be due to both above-mentioned factors: the changed status of the IM level and the record-to-record variability.

In the proposed method described in this paper, levels of IM are not increased with the GM record scaling, but the IM is intensified while both the spectral shape and motion duration of the employed earthquake records get changed for all selected or required IMs. In other words, two other sources of variability are also added to the ones existed in the standard IDA procedure. The first one is the spectral shape of the records associated with a specific IM level. In this case, although the level of seismic intensity is increased in the proposed methodology, the spectral shape of the GMs at each IM level is also changed and is not kept constant for all levels of IM. The next source of variability incorporated into the proposed framework is the motion duration of the records employed at a given level of IM. Consequently, at each given level of IM, we have a set of records possessing two distinctive characteristics: a median duration and a unique acceleration spectrum.

On the way to consider the variability of motion duration of the produced GMs at a given level of IM, it is revealed that PGA (or SA) are nonlinearly correlated and convoluted with the significant duration parameter of the ground motions anticipated at a specific site. It means that an earthquake with a naturally generated PGA corresponds to a significant duration. Hence, the linear scaling procedure used in frameworks such as IDA may disturb the natural characteristics of the selected motions since the duration of the scaled ground motion is not altered and kept as it was before. Moreover, the relationship between PGA (or SA) and significant duration has found to be an exponential form composed of a region with a steady growth rate, along the horizontal or PGA axis, that gets longer as shorter rupture distances are taken to be at work. Typically, this region has short earthquake duration for all events simulated for a specific rupture distance. Since the fact the mentioned region gets widened enough when a small value of rupture distance is selected for simulation procedure of the scenario events, the PGA and motion duration seems to be somehow uncorrelated for such near-source earthquakes. This is in general agreement with the physical concept of the earthquakes in which rather shorter ground motion duration would be expected for near-source ground shakings. Therefore, this may let us think of record scaling as a legitimate way of changing the level of intensity in case near-source ground motions are decided to be used in a dynamic procedure.

Since it is found that linear scaling of the ground motions without any attention to the motion duration can alter and maybe damage the inherent characteristics of the real motion, it is deduced that ground motion duration should be also regarded as the main record selection criteria. It is of paramount to note that this statement is in general agreement with the present and previous (Hancock and Bommer 2006) observations, indicating that duration of the ground motions has a significant influence on the structural responses.

6. Summary and conclusion

Previous researches have shown that motion duration can have a considerable influence on the structural demands. Nevertheless, motion duration is not still taken as the main criterion for the record selection procedure of dynamic analyses—including response history analysis as well as the IDA framework. In this case, a simulation-based procedure has been devised to explore the potential variability of ground motion duration versus a given level of amplitude-based intensity measure. With this information in hand, a duration consistent incremental dynamic
analysis is proposed through a simulation-based methodology. In this methodology, duration consistent ground motions are first generated according to the target acceleration spectra and motion duration. These targets which are employed to generate duration consistent ground motions are produced at all levels of intensity measure. It is crucial to add that attenuation relationships are the core part of this simulation-based method. Although these attenuation relationships are derived from previously recorded data, the outputs of this simulation method have been subjected to a verification procedure in this study. In this case, four real ground motions are randomly selected and verified against the data obtained from this simulation. In order to find the authenticity of the proposed method, produced duration consistent ground motions are then incorporated in the nonlinear seismic assessment. These motions are actually employed as input excitations in incremental seismic assessment frameworks such as IDA or response history analysis. The following results have been drawn:

1- It is shown that the motion duration might be nonlinerly correlated to a given level of amplitude-based intensity measure, i.e. the PGA or SA at a specific period of vibration. This means that each level of intensity measure in ground motions may be accompanied by a specific value of motion duration.

2- It is revealed that properties of simulated events, including fault types and different rupture distances, can also have certain impacts on the shapes as well as the other characteristics of developed relationship functions between duration and a given level of intensity measure. In this case, it is found that the variability of motion duration given a PGA can be of insignificant for events with short source-to-site distances, resulting in a nearly the same short duration on all levels of intensity measure.

3- For higher levels of seismic intensity (e.g. for SAs > 0.4g of the case study model), outputs of nonlinear seismic assessment procedures—the standard IDA and the proposed duration-consistent one—demonstrate that incorporation of duration-consistent ground motions may lead to a noteworthy impact on the results and increase the predicted displacement responses of considered structural models.

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