



SeSDA

Sequential Seismic Degradation Analysis

Structural design method for seismic sequences and service life using the

Ductility Degradation Law (DuDeL)

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Complete Method

SeSDA — Sequential Seismic Degradation Analysis

Internal Law

DuDeL — Ductility Degradation Law

Initial Acceptance Criterion

Residual capacity at the end of the service life $\geq 55\%$ of the original capacity

Abstract

Conventional seismic design generally evaluates structural response to individual seismic events. However, a real structure may experience multiple earthquakes during its service life, including mainshock–aftershock sequences involving strong aftershocks, as well as independent events of different magnitudes.

After each event, the structure may retain residual deformations and exhibit a partial loss of stiffness, strength, and energy-dissipation capacity; therefore, assuming that each new earthquake acts on an intact structure may not adequately represent its physical condition.

This paper proposes SeSDA — Sequential Seismic Degradation Analysis, a structural design and verification method that explicitly considers a sequence of earthquakes over an established service life. SeSDA preserves the degraded state of the structure after each event and uses it as the initial condition for the subsequent analysis.

As the central component of the method, DuDeL — Ductility Degradation Law — is proposed as a formula that transforms the attained ductility into an explicit reduction in yield capacity σ_y .

$$N_f(\mu) = 34.63 \left(\frac{15 - \mu}{\mu - 1} \right)^{2.6}, \quad 1 < \mu < 15$$

Where:

N_f = equivalent number of excursions that would lead to capacity exhaustion at a ductility μ ;

μ = attained ductility;

μ_u = ultimate reference ductility.

$$\sigma_{y,i} = \sigma_{y,i-1} - \frac{\sigma_{y,0}}{N_f(\mu_i)} \quad (1)$$

Where:

$\sigma_{y,i}$ = residual yield capacity after excursion or event i ;

$\sigma_{y,i-1}$ = immediately preceding residual capacity;

$\sigma_{y,0}$ = initial yield capacity;

$N_f(\mu_i)$ = equivalent number of excursions associated with ductility μ_i ;

μ_i = ductility of excursion i ;

i = excursion or event index.

The procedure enables successive nonlinear dynamic analyses using 2PIM-hPIM, Newmark, or other integration methods, updating the structural capacity

after each event. For service-life applications, SeSDA is proposed to be integrated with SERRA [1–6] for hazard characterization and with real seismic records or synthetic accelerograms generated using THEK-SER [7].

$$\frac{\sigma_{y,final}}{\sigma_{y,0}} \geq 0.55 \quad (2)$$

Where:

$\sigma_{y,final}$ = residual yield capacity at the end of the sequence;

$\sigma_{y,0}$ = initial yield capacity;

minimum residual-capacity fraction proposed as the acceptance criterion = 0.55

The main contribution of this work is to establish a structural design procedure based on capacity reduction due to fatigue caused by repeated ductile excursions of the structure over time: a deterministic model that directly connects ductility, capacity degradation, and sequential earthquake analysis.

Keywords: SeSDA; DuDeL; ductility; seismic degradation; residual capacity; seismic sequence; service life; multiple earthquakes; nonlinear analysis; SERRA; THEK-SER; 2PIM.

1. Introduction

A structure does not necessarily experience only one earthquake during its existence. It may be subjected to a mainshock followed hours or days later by significant aftershocks, or it may experience different earthquakes over several decades of service.

Most earthquake-resistant structural design methods focus on providing the structure with sufficient capacity to withstand the effects of a single earthquake; the probable acceleration of that earthquake is evaluated and the building is given the capacity to sustain those loads with a given level of safety. This assumption is not realistic.

The procedure presented in this paper opens the possibility of designing a structure by subjecting it to several, dozens, or hundreds of earthquakes and observing how much of its capacity remains intact at the end.

After an earthquake capable of producing inelastic excursions, the structure may retain only a fraction of the capacity available before the event. Therefore,

the second earthquake should act on a structure whose mechanical state depends on what the structure experienced in the past.

The problem of successive earthquakes has been studied previously. Shokrabadi, Burton, and Stewart [8] analyzed structures subjected to mainshock–aftershock sequences, while Park–Ang [9,10] and Ibarra–Medina–Krawinkler [11] developed cumulative damage and deterioration models. A state-of-the-art review by Rashid and Nishio (2024) [12] summarizes the assessment of structures under mainshock–aftershock sequences and confirms the relevance of prior damage to performance under subsequent events.

The models of Clough (1966) [13] and Takeda et al. (1970) [14] are fundamental precedents for degrading hysteretic models. The contribution of this work lies in an explicit formulation that transforms the attained ductility into a reduction in residual capacity that can be transferred to the next event.

2. Physical Problem

Consider initially an equivalent single-degree-of-freedom system subjected to seismic excitation.

$$m\ddot{u} + c\dot{u} + f_s(u, \dot{u}) = -m\ddot{u}_g(t) \quad (3)$$

Where:

m = equivalent mass;

u = relative displacement;

$\dot{u}$ = relative velocity;

$\ddot{u}$ = relative acceleration;

c = damping coefficient;

$f_s(u, \dot{u})$ = nonlinear resisting force;

$\ddot{u}_g(t)$ = ground acceleration as a function of time t ;

t = time.

$$\mu = \frac{u_{\max}}{u_y} \quad (4)$$

Where:

μ = ductility;

$u_{\max}$ = maximum attained displacement;

u_y = yield displacement.

The central question of SeSDA is: what resisting capacity should be assigned to the structure when the next earthquake occurs?

3. DuDeL – Ductility Degradation Law

DuDeL introduces N_f . N_f represents the equivalent number of excursions at a given ductility that would lead to exhaustion of the capacity considered by the model.

$$N_f(\mu) = 34.63 \left(\frac{15 - \mu}{\mu - 1} \right)^{2.6} \quad (5)$$

Where:

N_f = equivalent number of excursions that would lead to capacity exhaustion at a ductility μ ;

μ = attained ductility;

μ_{ult} = ultimate reference ductility;

4. Degradation of Yield Capacity: DuDeL Model

The relative damage associated with an excursion i is defined by $1/N_f(\mu_i)$, and the corresponding capacity reduction is applied to the initial capacity $\sigma_{y,0}$. The value $\sigma_{y,i-1}$ represents the residual capacity existing immediately before the new excursion or event.

$$\Delta D_i = \frac{1}{N_f(\mu_i)} \quad (6)$$

Where:

ΔD_i = increment of relative damage associated with excursion i;

$N_f(\mu_i)$ = equivalent number of excursions associated with μ_i ;

μ_i = ductility of excursion i;

i = excursion index.

$$\Delta \sigma_{y,i} = \frac{\sigma_{y,0}}{N_f(\mu_i)} \quad (7)$$

Where:

$\Delta \sigma_{y,i}$ = reduction in yield capacity produced by excursion i;

$\sigma_{y,0}$ = initial yield capacity;

$N_f(\mu_i)$ = equivalent number of excursions associated with μ_i ;

μ_i = ductility of excursion i.

$$\sigma_{y,i} = \sigma_{y,i-1} - \frac{\sigma_{y,0}}{N_f(\mu_i)} \quad (8)$$

Where:

$\sigma_{y,i}$ = residual capacity after excursion i;

$\sigma_{y,i-1}$ = residual capacity before excursion i;

$\sigma_{y,0}$ = initial capacity;

$N_f(\mu_i)$ = equivalent number of excursions associated with μ_i .

$$\sigma_{y,i} = \sigma_{y,i-1} - \frac{\sigma_{y,0}}{34.63} \left(\frac{\mu_i - 1}{15 - \mu_i} \right)^{2.6} \quad (9)$$

Where:

$\sigma_{y,i}$ = residual capacity after excursion i;

$\sigma_{y,i-1}$ = preceding residual capacity;

$\sigma_{y,0}$ = initial capacity;

μ_i = ductility of excursion i;

μ_{ult} = ultimate reference ductility.

Definitive DuDeL Formula

$$\sigma_{y,n} = \sigma_{y,0} \left[1 - \frac{1}{34.63} \sum_{i=1}^n \left(\frac{\mu_i - 1}{15 - \mu_i} \right)^{2.6} \right], \quad \sigma_{y,n} \geq 0 \quad (10)$$

Where:

$\sigma_{y,n}$ = residual capacity after n excursions;

$\sigma_{y,0}$ = initial capacity;

n = total number of excursions considered;

i = index of each excursion;

μ_i = ductility of excursion i;

the condition $\sigma_{y,n} \geq 0$ prevents negative capacities.

5. Initial Physical Interpretation of DuDeL

The expression produces little degradation at moderate ductility levels and a pronounced acceleration in capacity loss as the ultimate ductility is approached.

The region near $\mu \approx 12$ represents an extreme degradation condition.

Table 1. Loss of yield capacity per excursion as a function of ductility μ .

Ductility μ	Loss of $\sigma_{y,0}$ per excursion
4	$\approx 0.10 \%$
5	$\approx 0.27 \%$
6	$\approx 0.63 \%$
8	$\approx 2.9 \%$
10	$\approx 13.3 \%$
12	$\approx 84.7 \%$
14	capacity exhaustion

6. SeSDA – Sequential Seismic Degradation Analysis

SeSDA uses DuDeL as a mechanism for transferring the structural state between successive dynamic analyses. The structure therefore retains a mathematical memory of previous earthquakes.

$$\text{Sismo}_1 \rightarrow \mu_1 \rightarrow \text{DuDeL} \rightarrow \sigma_{y,1} \rightarrow \text{Sismo}_2 \rightarrow \mu_2 \rightarrow \text{DuDeL} \rightarrow \sigma_{y,2} \rightarrow \dots \quad (11)$$

Where:

Earthquake1 and Earthquake2 = successive seismic events;

μ_1 and μ_2 = ductilities obtained in each event;

DuDeL = Ductility Degradation Law;

$\sigma_{y,1}$ and $\sigma_{y,2}$ = residual yield capacities after the first and second events, respectively.

Capacity may also change during the same earthquake if DuDeL is applied at each plastic excursion.

7. Two Modes of DuDeL Application

SeSDA allows DuDeL to be applied at the end of each earthquake or within the dynamic analysis itself whenever a relevant yielding event or excursion is identified. The second mode allows capacity to degrade during the same record.

- Mode A: DuDeL at the end of each earthquake to transfer residual capacity to the next event.
- Mode B: DuDeL within the same earthquake, applied to relevant excursions/yielding events.

8. Numerical Integration Using 2PIM-hPIM

The initially proposed implementation uses 2PIM-hPIM as the nonlinear dynamic integration procedure. The same concept can be implemented using Newmark or other nonlinear integrators, thereby separating the physical hypothesis of SeSDA from the specific integration algorithm.

$$2PIM_1 \rightarrow DuDeL \rightarrow 2PIM_2 \rightarrow DuDeL \rightarrow 2PIM_3 \rightarrow \dots \quad (12)$$

Where:

2PIM1, 2PIM2, and 2PIM3 = successive nonlinear dynamic runs using 2PIM-hPIM;

DuDeL = law applied between runs to update residual capacity.

9. SeSDA Applied to Mainshock–Aftershock Sequences

A natural first application is the study of short mainshock–aftershock sequences. The residual capacity from the first event is explicitly used as the condition for the second, and so on. Hosseinpour and Abdelnaby (2017) [15] showed that accounting for damage from previous events significantly modifies the fragility of reinforced-concrete frames subjected to multiple earthquakes.

$$M7 \rightarrow \sigma_{y,1} \rightarrow M6.5 \rightarrow \sigma_{y,2} \rightarrow M6 \rightarrow \sigma_{y,3} \quad (13)$$

Where:

M7, M6.5, and M6 = representative seismic events of magnitudes 7, 6.5, and 6;

$\sigma_{y,1}$, $\sigma_{y,2}$, and $\sigma_{y,3}$ = residual capacities after each event.

10. SeSDA Applied over the Full Service Life

The second application extends the concept from hours or days to decades. Instead of verifying only a design earthquake, SeSDA proposes identifying the relevant earthquakes that may reasonably affect the structure during its service life and applying them sequentially. Turchetti et al. (2023) [16] explicitly studied damage accumulation in a structure subjected to multiple earthquakes during its service life, providing a direct precedent for cumulative multi-event assessment.

$$T_L = 50 \text{ años} \quad (14)$$

Where:

T_L = design service life; 50 years = duration adopted in the conceptual example.

$$M8 \rightarrow M7 \rightarrow M6 \rightarrow M5 \rightarrow M7 \rightarrow M8 \quad (15)$$

Each event must be represented by an excitation compatible with magnitude, distance, source, soil conditions, duration, and frequency content.

11. Integration with SERRA

SERRA [1–6] — Seismic Energy Release and Risk Assessment — is proposed as the regional seismic-hazard characterization component. For a service life T_L , SERRA and/or complementary probabilistic or deterministic analysis should enable occurrence scenarios to be established by magnitude class.

$$N_{M4}, \quad N_{M5}, \quad N_{M6}, \quad N_{M7}, \quad N_{M8} \quad (16)$$

Where:

N_{M4} , N_{M5} , N_{M6} , N_{M7} , and N_{M8} = expected numbers of magnitude 4, 5, 6, 7, and 8 events, respectively, during the service life considered.

12. Selection or Generation of Accelerograms

Earthquake magnitude alone does not constitute a time history of acceleration. For each scenario, compatible real records must be selected or representative synthetic records must be generated.

THEK-SER [7] is proposed as an option for reconstructing/generating accelerograms compatible with the selected spectral characteristics.

$$\text{SERRA} \rightarrow \text{escenarios sísmicos} \rightarrow \text{THEK – SER/registros reales} \rightarrow a_g(t) \quad (17)$$

13. Integrated SeSDA Architecture

The complete method integrates hazard characterization, motion selection or synthesis, nonlinear dynamic analysis, ductility evaluation, degradation through DuDeL, and transfer of the residual state to the next event.

$$T_L \rightarrow \text{SERRA} \rightarrow \{E_1, E_2, \dots, E_n\} \quad (18)$$

Where:

T_L = design service life;

$E_1, E_2, \dots, E_n$ = seismic events that make up the design sequence;

n = total number of events considered.

$$E_i \rightarrow a_{g,i}(t) \rightarrow (2PIM - hPIM) \rightarrow \mu_i \rightarrow \text{DuDeL} \rightarrow \sigma_{y,i} \rightarrow E_{i+1} \quad (19)$$

Where:

E_i = seismic event i ;

$a_{g,i}(t)$ = accelerogram of event i ;

2PIM-hPIM = dynamic integration procedure;

μ_i = ductility obtained in event i ;

DuDeL = degradation law;

$\sigma_{y,i}$ = residual capacity after event i ;

E_{i+1} = next event.

$$\text{SERRA} + \text{THEK} - \text{SER} + 2\text{PIM} - \text{hPIM} + \text{DuDeL} = \text{SeSDA} \quad (20)$$

Where:

SERRA = hazard characterization;

THEK-SER = accelerogram generation/reconstruction;

2PIM-hPIM = nonlinear dynamic integration;

DuDeL = degradation law;

SeSDA = Sequential Seismic Degradation Analysis.

14. Design Criterion Based on Residual Capacity

It is proposed that the structure not be evaluated exclusively on the basis of non-collapse during a given earthquake. An additional residual-capacity condition is introduced for the end of the entire service life.

$$\frac{\sigma_{y,\text{final}}}{\sigma_{y,0}} \geq R_{\min} \quad (21)$$

Where:

$\sigma_{y,\text{final}}$ = residual capacity at the end of the sequence;

$\sigma_{y,0}$ = initial capacity;

$R_{\min}$ = required minimum residual-capacity fraction.

$$R_{\min} = 0.55 \quad (22)$$

Where:

$R_{\min}$ = minimum residual-capacity fraction proposed as the initial acceptance criterion; 0.55 = 55% of the original capacity.

If $\sigma_{y,\text{final}} < 0.55 \cdot \sigma_{y,0}$, the structure DOES NOT COMPLY with SeSDA and must be redesigned until the requirement is met.

15. Design Procedure

The SeSDA procedure is carried out iteratively until the design seismic sequence has been completed and the final residual capacity has been verified.

1. Define the service life T_L .
2. Determine the seismic hazard using SERRA and/or complementary methods.
3. Establish the set of probable events $E=\{E_1, E_2, \dots, E_n\}$.
4. Assign each event a real or synthetic accelerogram using THEK-SER.
5. Define the equivalent structural system; first implementation: SDOF.
6. Define $\sigma_{y,0}$.
7. Apply the first accelerogram using 2PIM-hPIM.
8. Obtain μ_1 .
9. Apply DuDeL and obtain $N_f(\mu_1)$.
10. Update $\sigma_{y,1}$.
11. Apply the next earthquake using the preceding residual capacity.
12. Repeat until the sequence is complete.
13. Calculate $R_{\text{res}} = \sigma_{y,n} / \sigma_{y,0}$.
14. Verify $R_{\text{res}} \geq 0.55$.
15. If the criterion is not met, redesign and repeat SeSDA.

16. Difference from Classical Models

SeSDA seeks to provide an approach complementary to existing models. Takeda [14] and Clough [13] are precedents for hysteretic degradation, IMK [11] incorporates explicit strength and stiffness deterioration, and Park–Ang [9,10] recognizes the cumulative nature of damage. DuDeL introduces a direct relationship $\mu \rightarrow N_f \rightarrow \Delta\sigma_y$, and SeSDA extends that relationship to capacity transfer between successive events [17,18].

17. Relationship to Existing Degradation Models

DuDeL adopts ductility μ as its primary variable and, in its initial formulation, does not require integration of total hysteretic energy as a control parameter.

This simplicity facilitates its integration with dynamic methods in which maximum ductility is a natural output of the analysis.

18. Parametric Nature of DuDeL

The formulation should be understood as a parametric family. The values $\mu_{ult} = 15$, $p = 2.6$, and $C = 34.63$ correspond to the proposed calibration and may subsequently be modified without changing the conceptual structure of the law.

$$N_f(\mu) = C \left(\frac{\mu_u - \mu}{\mu - 1} \right)^p \quad (23)$$

Where:

$N_f(\mu)$ = equivalent number of excursions associated with ductility μ ;

C = calibration coefficient;

μ_{ult} = ultimate reference ductility;

μ = attained ductility;

p = exponent controlling the degradation rate.

$$C = N_r \left(\frac{\mu_r - 1}{\mu_u - \mu_r} \right)^p \quad (24)$$

Where:

C = calibration coefficient;

N_r = number of excursions at the reference point;

μ_r = ductility at the reference point;

μ_{ult} = ultimate reference ductility;

p = degradation exponent.

19. Residual Capacity during a Sequence

The normalized residual capacity $R_o = \sigma_y / \sigma_{y,0}$ can be used to graphically represent structural deterioration throughout the design service life and quantify the percentage of capacity consumed by each event.

$$R_{\sigma,i} = \frac{\sigma_{y,i}}{\sigma_{y,0}} \quad (25)$$

Where:

$R_{\sigma,i}$ = residual-capacity ratio after event i ;

$\sigma_{y,i}$ = residual capacity after event i ;

$\sigma_{y,0}$ = initial capacity.

20. Event Order

SeSDA allows different permutations of the same population of earthquakes to be analyzed. Event order may be critical because each event acts on a different residual capacity.

21. Future Performance Criteria

The value $R_{\min} = 0.55$ represents the first proposed acceptance condition. Future work may define different thresholds according to importance, structural type, and performance objective.

$$R_{\text{res}} \geq 0.55 \quad (26)$$

22. Service-Life Design Potential

The ultimate objective of SeSDA is to change the traditional question “Will the building withstand the design earthquake?” to “Can the building withstand its entire anticipated seismic life while retaining an acceptable residual capacity at the end?”

$$\mathcal{S}(T_L) \rightarrow \sigma_{y,\text{final}} \geq R_{\min} \cdot \sigma_{y,0} \quad (27)$$

Where:

$\mathcal{S}(T_L)$ = seismic sequence corresponding to service life T_L ;

$\sigma_{y,\text{final}}$ = residual capacity at the end of the sequence;

$R_{\min}$ = required minimum fraction;

$\sigma_{y,0}$ = initial capacity.

23. Discussion

The concepts of cumulative damage, degrading hysteretic models, and mainshock–aftershock analysis have extensive precedents. The specific contribution proposed by Moncayo Theurer is DuDeL as the explicit transformation $\mu \rightarrow N_f(\mu) \rightarrow \Delta\sigma_y$ and its integration within SeSDA to transfer residual capacity between successive events.

Based on the literature review conducted for this work, no published formulation with the same functional structure was found. The works of Hosseinpour and Abdelnaby (2017) [15], Turchetti et al. (2023) [16], and Rashid and Nishio (2024) [12] support the general problem of cumulative damage and seismic sequences without reproducing the specific functional formulation proposed for DuDeL.

As complementary context for Moncayo Theurer's research line, related works on attenuation laws, formula evolution and reduction, structural-period estimation, soil–structure interaction, and seismic and urban risk-assessment methodologies are included [19–29]. These references are provided as background and related methodological developments within the THEK ecosystem and are not presented as direct support for the specific DuDeL or SeSDA formulation.

24. Conclusions

1. SeSDA — Sequential Seismic Degradation Analysis — is proposed as a structural design and verification methodology focused on earthquake sequences and seismic assessment throughout the entire service life of a structure.
2. DuDeL — Ductility Degradation Law — constitutes the core degradation mechanism and makes it possible to explicitly preserve the memory of damage between earthquakes. The proposed THEK implementation integrates SERRA + THEK-SER + 2PIM-hPIM + DuDeL.
3. As an initial acceptance criterion, $\sigma_{y,final} \geq 0.55 \cdot \sigma_{y,0}$ is proposed. If this condition is not met, the structure must be redesigned and reassessed using SeSDA.

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