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Sensitivity of ground response analysis to dynamic soil models implemented in soft soil deposits

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ABSTRACT: Over the last two decades, an increasing number of dynamic soil models and numerical routines for ground response analyses have been proposed to enhance their implementation and improve their predictions. Nonlinear analyses are often computed using soil constitutive models that are consistent with the soil skeleton, but accept some inconsistencies in the energy dissipated by hysteresis that is represented using the Masing rules approach. This implicit formulation of soil damping in nonlinear analysis gives rise to some inconsistencies with laboratory test measurements, which in turn can result in an overdamping of the ground motions predicted. In this study, we evaluate the sensitivity of one-dimensional site response predictions to a range of dynamic soil models by comparing a nonlinear model computed in OpenSees against a modified equivalent linear method using frequency-dependent soil parameters that are consistent with both shear modulus reduction and soil damping curves from laboratory testing.

1 INTRODUCTION

Despite significant developments in one-dimensional (1-D) site response methods using nonlinear (NL) analysis, the Equivalent-Linear (EL) method first proposed by Seed and Idriss (1969) remains the most widely used approach by practitioners to investigate the total stress response of soil deposits. Reasons for this could be that NL methods are more sensitive to the input data (e.g. material properties) and analysis parameters (e.g. algorithm for time domain integration). While the EL method is implemented using both targeted shear modulus reduction and damping curves from laboratory test measurements, NL Cyclic Shear Stress (CSS) models are often computed using hyperbolic models to define the initial stress-strain loading, termed soil skeleton or backbone curve (e.g. Kondner & Zelasko 1963; Darendeli 2001), in conjunction with reversal shape functions that control the unloading-reloading path during cyclic shear stress loadings. The shape of the hysteresis loops, commonly implemented using the Masing rules (Masing, 1926) or a similar approach, constrains the energy dissipated during the analysis.

Some inconsistencies inherent to the implementation of nonlinear soil models are:

(1) The implicit formulation of energy dissipation through the use of hysteretic shape functions can introduce noticeable discrepancies as compared with soil damping curves obtained from laboratory test measurements (Meite et al., 2018).

(2) Dynamic soil models using laboratory test data are often constrained by low to moderate shear strain measurements (e.g. Darendeli model, 2001). A common practice when simulating strong ground motions is to modify the shape of the backbone curve to match the shear strength at large strains. The bias introduced in NL response implemented with extended hyperbolic soil models to simulate large shaking are not well understood.

(3) Because the hysteresis loops employed in NL CSS models produce zero energy dissipation at low strains where the secant shear modulus is almost linear, a viscous damping component is generally introduced into the model using the full Rayleigh formulation targeted to match the small soil damping ratios commonly observed at low strains. However, this approach requires a cautious calibration at the elastic level that can be inconsistent when higher degree of nonlinearities develop during the analysis.

This paper provides an insight into the sensitivity of nonlinear ground response analyses to well-selected dynamic soil models commonly employed in earthquake engineering practice, these include: the Kondner & Zelasko model (1963) also termed as KZ model; the modified KZ model by Matasovic & Vucetic (1993a) referring to as MKZ model; and the Darendeli model (2001) modified to be strength-compatible at large strain. A series of 1-D site response analyses were conducted using both a nonlinear CSS Masing-type model computed using OpenSees (Mazzoni et al., 2010), and a modified equivalent-linear method using frequency-dependent soil parameters to better capture nonlinear effects.

2 GROUND MOTION SELECTION

A suite of 10 records consistent with a rock site class B condition as defined in the NZ1170.5 (2004) loadings standard were selected and used as control motions. Selection was made across range of source mechanisms for crustal earthquake scenarios along with a set of motion intensities suitable for performing site response analyses. One half of the records were sourced from the Pacific Earthquake Engineering Research Center ground motion database (PEER, NGA-West2) and the other half are from the New Zealand database GeoNet developed by GNS Science. These records comprise recent seismic events in New Zealand from the 2010-2011 Canterbury earthquake sequence and the Kaikoura earthquake (2016), all recorded from stations that exhibit rock site class B conditions. A scaling factor was applied to the time-history records to match the PGA of the Uniform Hazard Spectrum (UHS) defined in the NZS1170.5 standard (Z=0.25, R=1, N=1). Figure 1 shows the pseudo-response spectra of the 10 records and the geometric mean response spectrum compared to the UHS spectrum.

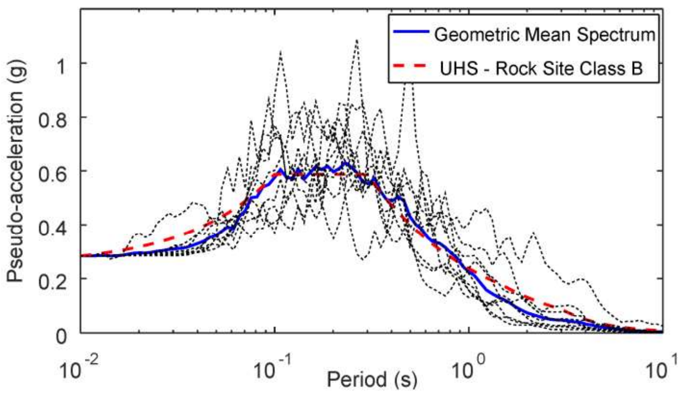

Figure 1. Record response spectra with PGA scaled on normalized UHS rock spectrum, site class B, according to NZ1170.5 (2004) standard – Spectral shape factors: Z=0.25, R=1, N=1.

3 SOIL PROFILE MODELS

3.1 *Shear-wave velocity profile*

1-D site response analyses were carried out considering two local site conditions that would be classified as site class C and D according to NZ1170.5 (2004), which characterizes respectively a shallow soil site and a deep soil deposit. The shear wave velocity profiles were defined for multi-layered soil systems consisting of loose to dense sand in a drained condition suitable for performing a total stress analysis. Details of the soil profiles are summarized in Table 1.

3.2 *Kondner & Zelasko (1963) – KZ model*

The original hyperbolic relationship between shear stress (τ) and shear strain (γ) formulated by Kondner & Zelasko (1963) was an important step forward in nonlinear codes as this model can be readily computed as follows:

$$\tau = \frac{\gamma}{\frac{1}{G_{max}} + \frac{\gamma}{\tau_{max}}} \tag{1}$$

where G_{max} is the elastic shear moduli at low strain, and τ_{max} represents an upper boundary of shear stress conveniently associated with the soil strength.

By rearranging the previous equation, shear modulus degradation ratios can be derived so that:

$$\frac{G}{G_{max}} = \frac{1}{1 + \frac{\gamma}{\gamma_{ref}}} \tag{2}$$

where γ_{ref} refers to as a reference shear strain equal to τ_{max}/G_{max}.

3.3 *Matasovic & Vucetic (1993a) – MKZ model*

To better capture the effect of nonlinearities using a stress-strain hyperbolic model, Matasovic & Vucetic (1993a) among others proposed additional curve fitting parameters, herein β and *s*, to adjust the original KZ model so that the hyperbolic relationship becomes:

$$\frac{G}{G_{max}} = \frac{1}{1 + \beta\left(\frac{\gamma}{\gamma_r}\right)^s} \tag{3}$$

Another major feature in this model is that the reference strain γ_r is well-adjusted so that:

$$\gamma_r = \frac{\tau_{mo}}{G_{max}} \tag{4}$$

where τ_{mo} is a trade-off value of maximal stress which is lower than the shear strength but greater than the stresses expected to occur during the shaking. This process allows the hyperbolic model to better capture soil nonlinear effects over a moderate shear strain range not exceeding 1-3%, as generally observed in ground motions records.

Table 1. Characterization of site profile used for 1D site response analysis

Site Class*	Site Period (s)	$V_{s,30}$** (m/s)	Description	Top of layer (m)	Layer Thickness (m)	Density (kg/m^3)	V_s (m/s)	Friction Angle (°)
C	0.46	259	Medium Sand - Dr=50%	0.0	5.00	1.8E+03	201	33
			Medium-Dense Sand - Dr=70%	5.0	5.00	2.0E+03	221	39
			Medium-Dense Sand - Dr=80%	10.0	5.00	2.0E+03	241	41
			Dense Sand - Dr=90%	15.0	5.00	2.1E+03	288	44
			Dense Sand - Dr=90%	20.0	5.00	2.1E+03	317	44
			Dense Sand - Dr=90%	25.0	5.00	2.1E+03	346	44
D	0.88	188	Loose Sand - Dr=30%	0.0	7.50	1.7E+03	165	28
			Medium Sand - Dr=50%	7.5	7.50	1.8E+03	181	33
			Medium Sand - Dr=50%	15.0	7.50	1.8E+03	197	33
			Medium-Dense Sand - Dr=70%	22.5	7.50	2.0E+03	219	39
			Medium-Dense Sand - Dr=80%	30.0	7.50	2.0E+03	241	41
			Dense Sand - Dr=90%	37.5	7.50	2.1E+03	263	44

Note: * Site Class according to NZS1170.5 standard
* * $V_{s,30}$ denotes the time-averaged shear wave velocity to 30 m depth

In this study, the parameters used to set up the MKZ model for sand were the following:

- $\beta = 1.5$; $s = 0.86$
- τ_{mo} was derived from Equation 1 using an arbitrary value of shear strain equal to 1%.

3.4 *Darendeli model (2001), strength corrected*

The Darendeli model is best suited to represent small-strain dynamic soil properties. This model relies on the hyperbolic relationship of shear modulus degradation expressed as follows:

$$\frac{G}{G_{max}} = \frac{1}{1+\left(\frac{\gamma}{\gamma_r}\right)^a} \tag{5}$$

where γ_r is a reference strain and a denotes a curvature coefficient. In particular, these two parameters are defined as a function of the soil type and plasticity index (*PI*), the over-consolidation ratio (*OCR*), the confining pressure ($\sigma_0^{'}$) and also a series of model calibration parameters ($\varnothing_i$) obtained from a regression analysis conducted over range of experimental data measurements. Finally the reference strain is defined so that:

$$\gamma_r = \left(\varnothing_1 + \varnothing_2 * PI * OCR^{\varnothing_3}\right) * \sigma_0^{'\varnothing_4} \tag{6}$$

Importantly, the Darendeli model is constrained by laboratory test data using range of shear strain values below 0.5%. Therefore, some inconsistencies appear when this model is used to model strong earthquakes that exhibit larger strain amplitudes. In such cases, the level of stress is found to be greater than the soil shear strength and the ground response model is biased. To address this drawback, a common practice consists of artificially modifying the shape of the hyperbolic backbone curve to represent a consistent shear strength at larger strains. Many procedures have been proposed to address this issue. In this study, we used the strength-compatibility procedure proposed by Gingery and Elgamal (2013) to correct the Darendeli shear modulus reduction curves. This model is then referred to as the hybrid-Darendeli model.

Acknowledging that the energy dissipation based on Masing behaviour along with the proposed shear modulus degradation model is a poor trade-off when compared with soil damping values measured in laboratory tests, Darendeli corrected the Masing-based damping model (D_{Masing}) by applying scaling factors along with curve fitting parameters to provide a consistent soil damping model such as:

$$D_{Adjusted} = b * \left(\frac{G}{G_{max}}\right)^{0.1} * D_{Masing} \tag{7}$$

In this study, the parameters used to set up the Darendeli model for sand were the following:

- $PI = 0$; $OCR = 1$
- $\varnothing_1 = 0.0352$; $\varnothing_2 = 0.0010$; $\varnothing_3 = 0.3246$; $\varnothing_4 = 0.3483$; $a = \varnothing_5 = 0.9190$; $b = 0.6066$

3.5 *Soil model comparison*

The aforementioned hyperbolic CSS soil models were implemented and compared considering a medium dense sand material with a relative density of 50%. Figure 2a depicts the shear modulus degradation curves across all soil models, along with the corresponding backbone curves shown in Figure 2b. One should keep in mind that the MKZ model lies between the Darendeli model, that exhibits stronger decay in shear modulus across all strain amplitudes, and the KZ model that displays a stiffer soil behaviour when subject to shearing. In this example, the hybrid-Darendeli model, modified to be strength-compatible, overlaps the MKZ model around 5% shear strain and meets the KZ curve at large strains.

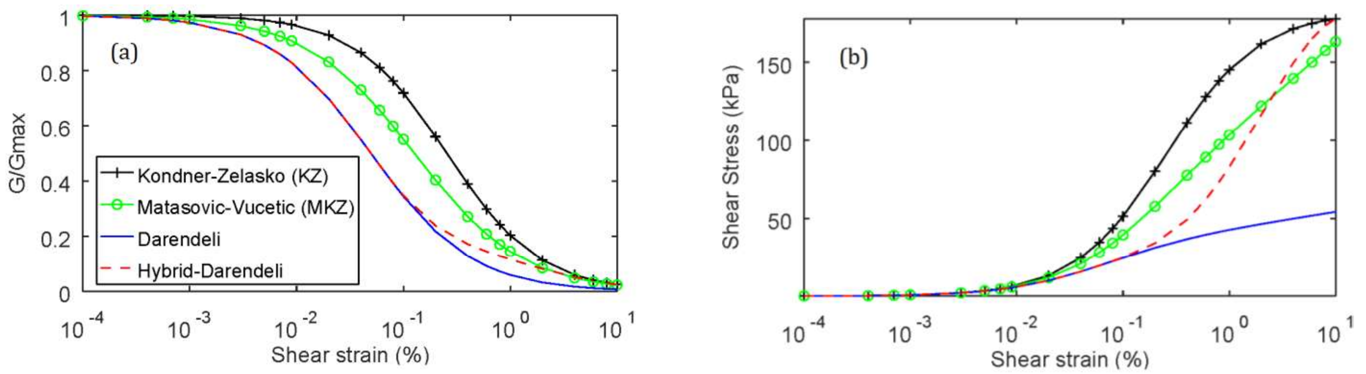

Figure 2. Comparison of hyperbolic curves for sand: (a) shear moduli reduction curves and (b) backbone curves. The soil parameters considered for all models were: G_{max} = *71 349 kPa – Internal friction angle = 33° - Confining pressure =274 kPa*.

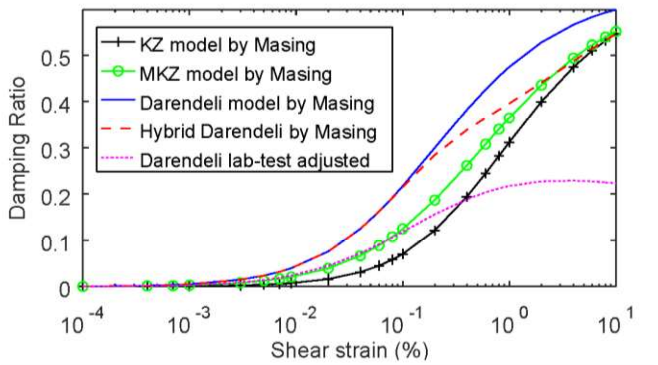

Figure 3. Comparison of soil damping curves for sand for Masing-based models and a laboratory consistent damping curve obtained from Darendeli model (2001).

The Masing-based soil damping curves were derived from shear modulus reduction ratios for each model using the following relationship:

$$D_{Masing} = \frac{\pi}{4}\frac{1}{1-G/G_{max}}\left[1+\frac{G/G_{max}}{1-G/G_{max}}ln\left(\frac{G}{G_{max}}\right)\right]-\frac{\pi}{2} \tag{8}$$

The inferred Masing-based damping curves across all hyperbolic models are compared in Figure 3 against a laboratory consistent damping curve as proposed by Darendeli in Equation 7. As expected, the Darendeli Masing-based damping model, even after strength correction, is significantly over-predicted as compared with the laboratory consistent curve. Moreover in this example, at low to moderate strains, say below 0.1%, the MKZ model is in accordance with the laboratory damping curve by Darendeli while the KZ model tends to be underdamped. At large strains, both MKZ and KZ models depart from the laboratory damping curve and over-predict the energy dissipated.

4 GROUND RESPONSE ANALYSIS

4.1 *Time domain nonlinear analysis*

A soil column model was implemented in OpenSees to model nonlinear 1-D site response using a finite element continuum model constrained to convey horizontal stresses when a horizontal base motion is applied. The model consists of quadrilateral elements with two degrees-of-freedom and a plane strain formulation. As is recommended when using outcropping records as control motions, part of the strain energy transmitted within the bedrock interface should be dissipated, herein using a viscous dashpot at the base of the soil column (Lysmer-Kuhlemeyer 1969).

Total stress analyses were performed using the Pressure Independent Multi-Yield (PIMY) model in OpenSees (Mazzoni & al. 2010) to simulate the deviatoric stress-strain soil response under a monotonic or cyclic loading. The plastic stress behaviour implemented is based on the multi-yield surfaces framework (Prevost 1985) and further modified (Parra 1996, Yang 2000). The KZ hyperbolic backbone curve can be generated automatically in the PIMY material model using a built-in hyperbolic relationship between the shear strain and the shear stress. Alternatively, OpenSees allows the implementation of user-specified modulus reduction ratios over a finite number of yield surfaces. In this study, the aforementioned shear modulus degradation models were generated for each soil element according to the confining pressure over depth. Importantly, the energy dissipation in the constitutive CSS soil model is constrained by the shape of hysteresis loops following the Masing rules, and therefore differs from laboratory soil damping curves.

4.2 *Frequency domain equivalent-linear analysis with frequency-dependent soil parameters*

In order to better capture soil nonlinear effects while using frequency domain analysis, the original EL method, that has been shown to attenuate the higher frequency components of ground motions, has been modified by using both frequency-dependent soil moduli and soil damping ratios. This procedure is commonly termed the Frequency-Dependent Equivalent Linear (FDEL) method. In this study, a new FDEL approach was implemented and tested to generalize the numerical scheme over a range of ground motion intensities and frequency content and to simplify its computation through the EL iterative procedure. Previous FDEL formulations available in the literature (Kausel & Assimaki, 2002; Yoshida & al, 2002) are based on observations of the Fourier response of the shear strain along with calibrated parameters to adjust the prediction over frequencies of interest. The proposed FDEL method relies on the Fourier Transformation (*FT*) of the instantaneous elastic power stress scaled on the maximal shear strain as a proxy for the frequency-dependent effective shear strain expressed as followed:

$$\gamma_{eff}(\omega) = \gamma_{max} \frac{FT\left[G(t)\gamma(t)\dot{\gamma}(t)\right]}{\max\left\{FT\left[G(t)\gamma(t)\dot{\gamma}(t)\right]\right\}} \quad (9)$$

where the component $G(t)\gamma(t)$ represents the elastic shear stress and $\dot{\gamma}(t)$ denotes the strain rate.

The advantage of this approach is that it is readily computable in a routine implemented within the EL iterative procedure and no additional calibration parameters were used for the model prediction. More importantly, the proposed formulation appears to be more reliable than the existing FDEL methods that were found to display unrealistic departures in ground response spectral accelerations when motions that exhibit high frequency content are simulated (Hartzell, 2004).

5 RESULTS AND DISCUSSION

Nonlinear 1-D ground response analyses were performed in OpenSees using the aforementioned set of hyperbolic backbone curves, herein comparing the KZ model, the MKZ model and the hybrid-Darendeli model (Fig. 2). While nonlinear models were implemented along with the Masing rule-based damping approach, frequency domain analyses were computed through the FDEL procedure, using both targeted shear modulus reduction and damping curves as proposed in the Darendeli lab-test adjusted model (Fig. 3).

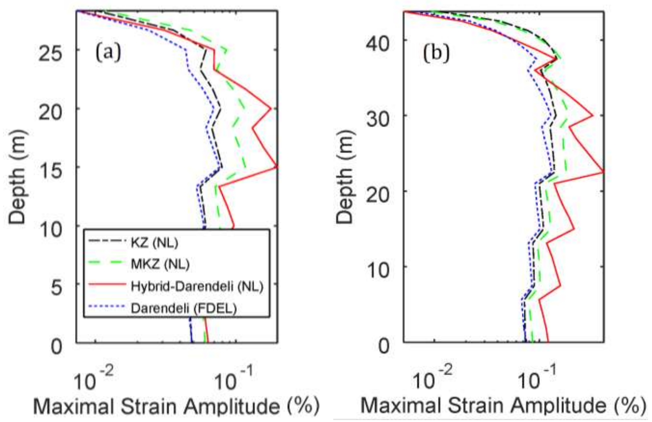

Figure 4. Comparison between the geometric mean predictions of peak shear strains obtained across all methods within both soil profiles: (a) site class C and (b) site class D profile (NZS1170.5, 2004).

Figure 4 shows the peak shear strain predictions across all models that were calculated in both soil profiles for site class C and D conditions. A clear outcome when comparing all model predictions is that the NL response using the hybrid-Darendeli model exhibits higher peaks of shear strain over depth as compared with other hyperbolic models whose the dynamic soil properties decay less rapidly when sheared, suggesting a potential for over-prediction of nonlinear effects and numerical instabilities when strong earthquakes are simulated.

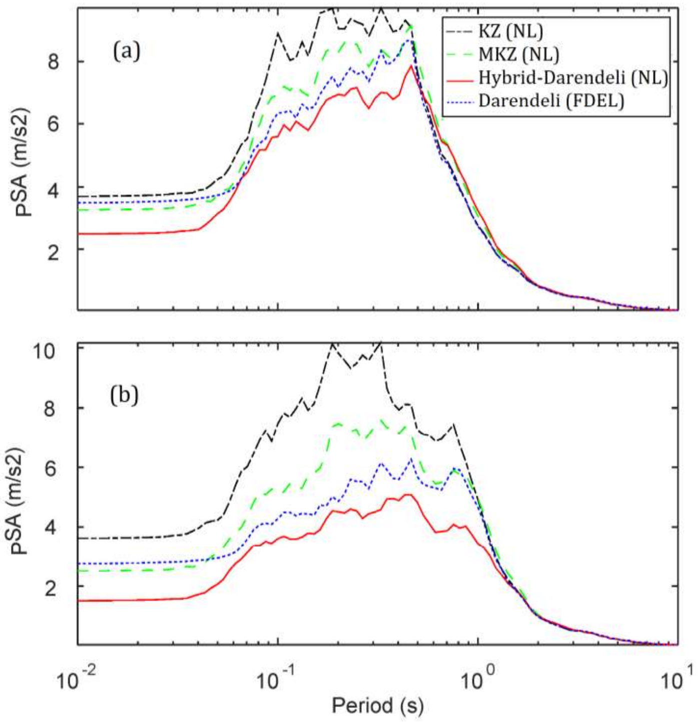

Figure 5. Comparison between the geometric mean response spectra in acceleration across all models, obtained in both soil profiles: (a) site class C and (b) site class D profile (NZS1170.5, 2004).

In Figure 5, we compare all model predictions in terms of the geometric mean pseudo-spectral acceleration (pSA) at the ground surface for all ground motion records. The FDEL model that is consistent with the laboratory-based soil data characteristics was used as a baseline for comparison against nonlinear Masing-based models. The main outcomes are summarized below:

1. Nonlinear analyses using strength-based backbone curves as proposed in the KZ model, may tend to under-damp the ground response motions, especially when the range of shear strains that develop within the soil profile is below failure.
2. In contrast, NL Masing-based models may predict ground motion intensities that are substantially over-damped even at low to moderate shear strain, as compared with the frequency-domain FDEL method using

laboratory consistent damping curves by Darendeli. Clearly, when using Masing-based CSS model in NL analysis for the purpose of investigating site amplification effects, the hybrid- Darendeli model, that was modified to be strength-compatible, may have issues related to energy dissipation.

3. In an attempt to utilize hyperbolic shear modulus reduction models that account for the inherent over-damping due to Masing behaviour, the MKZ model provides the best trade-off when all solutions are compared against the FDEL model implemented with consistent dynamic soil properties. A key requirement to set up the MKZ model is the use of appropriate hyperbolic curve fitting parameters that provide good agreement with experimental observations at moderate level of shear strains expected to develop during the analysis, rather than matching with an upper bound in line with the shear strength at failure.

6 CONCLUSIONS

A comparative study was carried to gain insights into the sensitivity of 1-D site response predictions to range of dynamic soil models commonly employed to simulate soil nonlinearity effects. One should keep in mind that when performing site response analysis, nonlinear methods are much more sensitive to the set of input dynamic soil parameters as compared with frequency domain methods. The variability inherent in the choice of these input soil models becomes greater in soft soil deposits where higher strain deformations develop during the ground motion simulation. Therefore, dynamic soil models should be selected with due consideration to the degree of soil nonlinearity expected in conjunction with the seismic intensities. More investigations are needed to assess the inherent bias introduced by these hyperbolic soil models in site response predictions as compared with historical vertical downhole seismometer array data.

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