



Parametric study of supplemental viscous damping combined with seismic isolation in Wellington

D. Whittaker & D. Marriott

Beca Ltd, Christchurch, New Zealand.

N. Canney & B. Covich

Taylor Devices Inc., Reno, U.S.A.

ABSTRACT

A parametric study examines the benefits of adding viscous damping to the isolation plane and in the superstructure of base-isolated buildings to reduce structural response. The study includes impacts of the recently increased seismic hazard (TS 1170.5) in Wellington, which will challenge the practical limits of world leading facilities to test isolation devices. Parameters included in the study include isolation system parameters (yield level and second slope stiffness) and level of viscous damping added to the isolation layer and superstructure. Numerous nonlinear response history analyses were completed considering the chosen parameter ranges on a simple unitized one and two degree of freedom structural models using spectrally matched input ground motions. Building response performance is examined in terms of displacement demands on the isolation system, drift and floor acceleration response spectra in the superstructure. The parametric study shows that increased displacements in the isolation system and drifts in the superstructure due to TS 1170.5 increases can be neutralised by adding supplemental viscous damping in the isolation system and superstructure. Increased acceleration demands on the superstructure can be controlled to some extent but not neutralised.

1 INTRODUCTION

This paper investigates the benefits of adding viscous damping to typical base-isolated structures to reduce structural response and protect the superstructure in high seismicity locations. The first author (Whittaker 2024) carried out a similar study with variable levels of viscous damping added to a simple base-isolation model at a moderate seismicity location. Seismic isolation (normally “base-isolation” installed at the base of a structure), and supplemental damping are both effective technologies for protection of structures. In high seismicity locations, including near active earthquake faults, displacement demands on isolation systems can

become large. The recently revised New Zealand National Seismic Hazard Model (GNS 2022) has now been incorporated as design spectra within Technical Specification TS 1170.5 (Standards NZ, 2025). The document specifies acceleration and displacement spectra across the country and seven Site Classes, based on time-averaged shear wave velocities in the upper 30m depth of soil $V_{s(30)}$, ranging from very stiff Site Class I Rock ($V_{s(30)} > 750$ m/s) to a very soft Site Class VII ($V_{s(30)} < 150$ m/s). The recommended spectra for high seismicity locations and soft ground conditions lead to significantly greater demands on isolated structures in many locations compared with the current design Standard NZS 1170.5. Some practitioners have commented that these demands will be difficult or uneconomic to design for using conventional seismic isolation alone. This study examines whether it is feasible to mitigate the increases in displacement and acceleration demands using supplemental viscous damping devices added in the isolation plane and/or in the superstructure.

2 PARAMETRIC MODEL AND VARIABLES

A single degree of freedom (SDOF) model was developed with a range of characteristics matching typical low-rise (say 2-4 storey) buildings supported on base-isolation. A unit weight of 1 kN was chosen, and other mass and stiffness parameters were selected to match realistic global dynamic characteristics. The model was also extended to a two degree of freedom (2DOF) to examine in more detail response characteristics (drift and floor acceleration spectra) of the superstructure. The SDOF and 2DOF models, weight, stiffness and global damping characteristics are summarized in Figure 1, including selected constant structural properties.

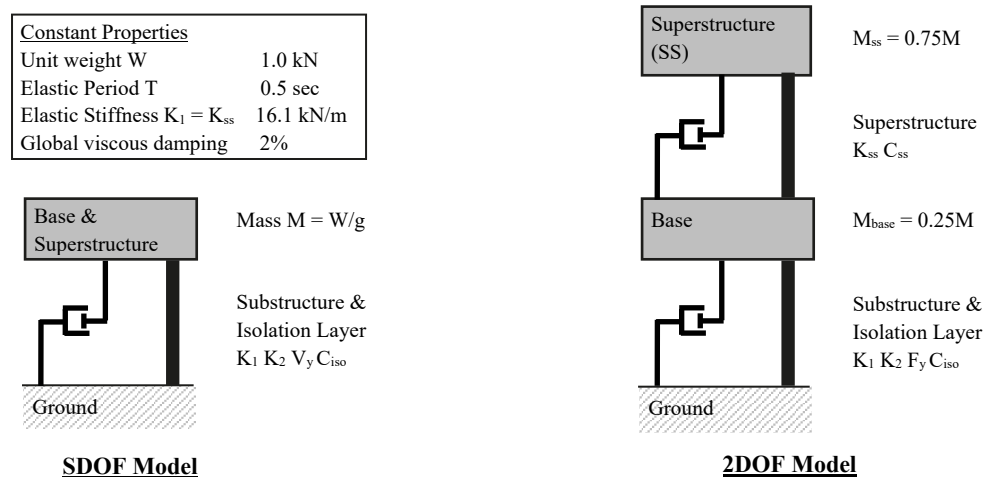


Figure 1. Simplified structural models for dynamic analysis: SDOF and 2DOF

For the SDOF model all of the mass above the ground level was assigned to the combined “Base and Superstructure” degree of freedom. The single vertical element is a simple bilinear shear element representing the ground floor structure and isolation system. The system shear stiffness K_1 represents overall stiffness of the structure and pre-yield stiffness of the isolators, while the second stiffness after yield K_2 represents the isolator post-yield stiffness. The post-yield stiffness can also be normalised to an equivalent post-yield period T_2 using the normal stiffness, mass and period relationship. The isolator yield force ratio V_y/W was varied (0.05, 0.1, 0.15 and 0.20). The damping coefficient of the parallel viscous damper was also varied to represent from zero to 50% of critical viscous damping (Damping Coefficient $C = \zeta 2M\omega$) with a damping velocity exponent α of 1.0 or 0.4 (damping force $F_d = C v^\alpha$). Global viscous damping of 2% of critical was also included in the model, applied as constant modal damping.

The 2DOF model in Figure 1 is an extended version of the SDOF model, with a “Superstructure” (SS) degree of freedom added above the “Base” degree of freedom. The “Base” degree of freedom was assigned 25% of the total mass and the “superstructure” degree of freedom assigned 75%, representative of the mass distribution in say a four-level building. The superstructure was modelled as an elastic shear element and a parallel viscous damping element.

The present study considered the following range of parameters:

- a) Wellington location assuming stiff or dense soil (Site Class III, $300 \text{ m/s} < V_{s(30)} < 450 \text{ m/s}$)
- b) seismic demands to (DZ) TS 1170.5:2025 and comparison with NZS 1170.5:2004
- c) comparison of demands for IL4 (eg a large hospital) and IL2 (normal importance) building
- d) isolation yield force to building weight ratio (V_y/W) of 0.05, 0.10, 0.15 and 0.20
- e) second slope periods T_2 of 2, 4 and 6 seconds ($T_2 = 2\pi \sqrt{M/K_2}$)
- f) added viscous damping to isolation C_{iso} corresponding to 0%, 5%, 10%, 30% and 50% of critical
- g) added viscous damping to superstructure C_{ss} approximating 0%, 0.5%, 5%, 50% of critical
- h) viscous damping exponents of 1.0 and 0.4 in both the isolation level and superstructure added damping.

3 ANALYSIS METHODOLOGY

The parametric analysis methodology is summarised in the following sequence.

- a) Acceleration response spectrum determined in accordance with TS 1170.5 (the draft DZ document was used for this study) or NZS 1170.5 for a Wellington location with Site Class III ground conditions.
- b) generate spectrally matched ground motions (using default El Centro 1940 N-S record in ETABS)
- c) vary the selected input parameters and run nonlinear response history analysis
- d) record the following response parameters:
 - i. maximum displacement of isolated base and superstructure (not simultaneous)
 - ii. maximum instantaneous drift of superstructure relative to base level above the isolation
 - iii. maximum isolation shear force, viscous damper force, base shear
 - iv. maximum ground, base level and superstructure acceleration and acceleration floor spectra
 - v. damping contributions: global, viscous, hysteretic and total energy dissipated

4 SDOF RESULTS SHOWING DEMANDS ON ISOLATION SYSTEM

Figure 2 (left) shows a selection of peak acceleration and displacement demands from the SDOF model for supplementary viscous damping in the isolation system. The maximum isolator shear ratio (shear force divide by isolated weight) and displacements are plotted for each isolation yield level and second slope stiffness (expressed as a period T_2). For each yield and second-slope period combination, the displacements and accelerations reduce substantially with increasing added viscous damping (reading the sloping lines from right to left in the Figure). The displacement of the isolation system can typically be halved by adding 10% viscous damping, but with more damping added the damping forces increase and may become difficult to design for in a real structure. Figure 2 (right) shows an example of isolator ($F_y/W = 0.2$) and viscous damper (and $C_{iso} = 0.256$, $\alpha_{iso} = 1.0$) forces versus displacement of the isolation. The maximum damper force (0.41 kN) is already somewhat greater than the maximum isolator force (0.3 kN).

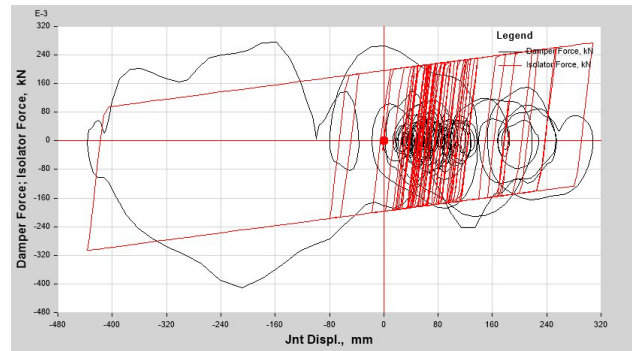
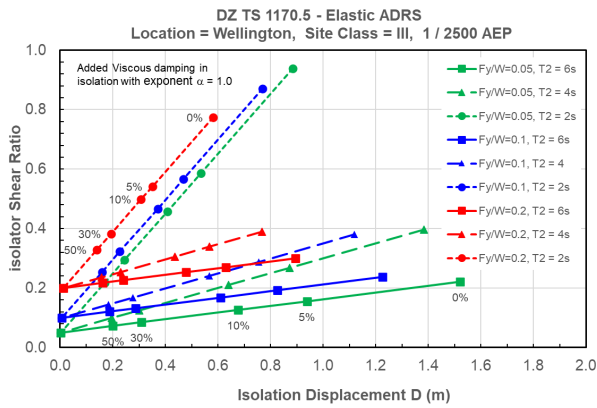


Figure 2. Left shows isolator force and displacement responses for various V_y/W , T_2 and supplementary viscous damping in isolation plane. Right shows isolator (Red) and viscous damper force (Black) versus isolation displacement for an example with $V_y/W=0.2$ and $T_2 = 4s$.

Figure 3 shows displacement demands in the isolation system with 0% to 50% added viscous damping using (DZ) TS 1170.5, NZS 1170.5 demands for 1 in 2500 years, and TS 1170.5 demand for 1 in 500 years. The dramatic increase in isolation displacement demands of the TS 1170.5 compared with NZS 1170.5 is evident. However, the diagram also suggests adding around 20% viscous damping (for this example) would reduce the TS 1170.5 displacement demands to about the same (450mm) as for NZS 1170.5.

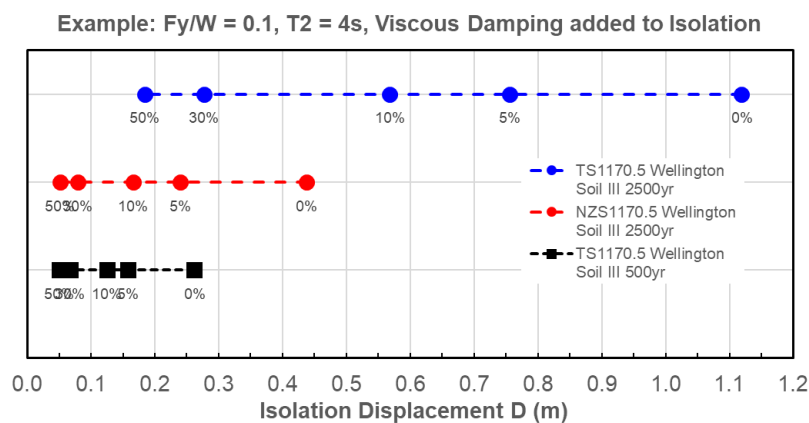


Figure 3. Isolation displacement demands with supplemental viscous damping in the isolation layer for TS 1170.5 1 in 2500 year (Blue), NZS 1170.5 1 in 2500 year (Red), TS 1170.5 1 in 500 year (Black).

5 DEMANDS ON SUPERSTRUCTURE USING 2DOF MODEL

Figure 4 (left) shows an example of maximum displacements of the base level and superstructure. The results are consistent with Figure 2, showing substantial reduction peak displacements as a result of adding viscous damping to the isolation layer, noting that maximum nodal displacements do not occur simultaneously.

Figure 4 (right) shows the corresponding superstructure inter-storey drifts expressed as a % of storey height for a base isolation system with $F_y/W = 0.1$ and $T_2 = 2s, 4s$ and $6s$ for various amounts of added viscous damping in the isolation layer. These results indicate that adding a small amount of viscous damping to the isolation layer for some cases will reduce the superstructure drift but adding substantial damping to the isolation will (undesirably) increase the superstructure drift.

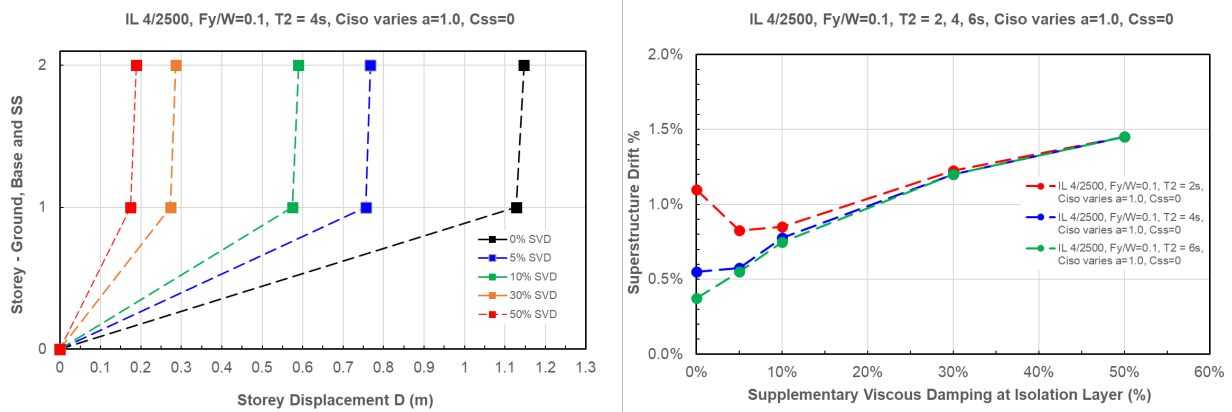


Figure 4. Displacements of 2DOF model for an example structure ($F_y/W = 0.1$) with various levels of supplemental damping in the isolation layer. Left shows maximum displacements at the base level and superstructure for $T_2 = 4s$. Right shows superstructure drift above base level for various added damping.

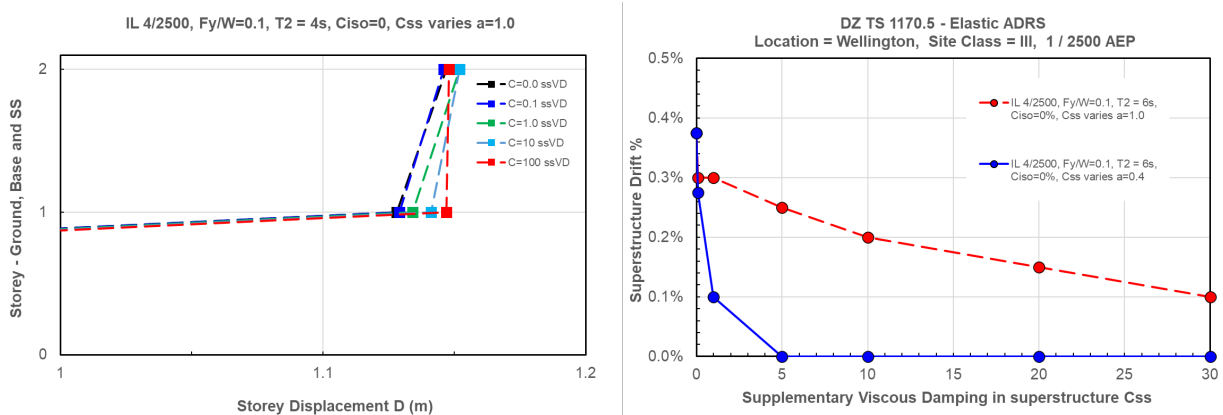


Figure 5. Displacements of 2DOF model for an example structure ($F_y/W = 0.1$) with various levels of supplemental damping in the superstructure. Left shows maximum displacements at the base level and superstructure. Right shows maximum superstructure drift above base level for various added damping.

Figure 5 shows maximum displacements and drifts of an example with viscous damping added to the superstructure with no viscous damping added to the isolation layer. The left-hand figure shows that the large isolation displacements are relatively insensitive to damping being added to the superstructure. The right-hand figure shows that superstructure inter-storey drifts can be reduced by adding viscous damping to the superstructure. A damping exponent of 0.4 appears to be much more effective at reducing the drift than an exponent of 1.0. Adding a large amount of viscous damping to the superstructure reduces drifts, as expected, because adjacent floors are forced to move together.

Figure 6 and 7 show examples of floor acceleration spectra (“Floor Spectra”), obtained by processing the 5% damped acceleration spectra from the absolute acceleration response histories at the base and superstructure levels. The plots also show the base level response spectrum (blue trace) representing the acceleration response spectrum of the ground motion record input to the model. Figure 6 left shows acceleration spectra for an isolated structure with no viscous damping added to the isolation layer or the superstructure. It shows the ground motion spectrum, floor spectra at the base level (orange trace) and at the superstructure node (green trace). The figure shows that over most of the period range between 0.5 seconds and 3 seconds there is a substantial reduction of acceleration response spectra in both the base level and superstructure floors as a result of the isolation system, however there is little reduction of acceleration response at short and long periods. Figure 6 right shows superstructure floor spectra for a system with 10% viscous damping added to

the isolation system. The “floor spectra” show an (undesirable) increase in floor acceleration spectra when viscous damping is added to the isolation layer.

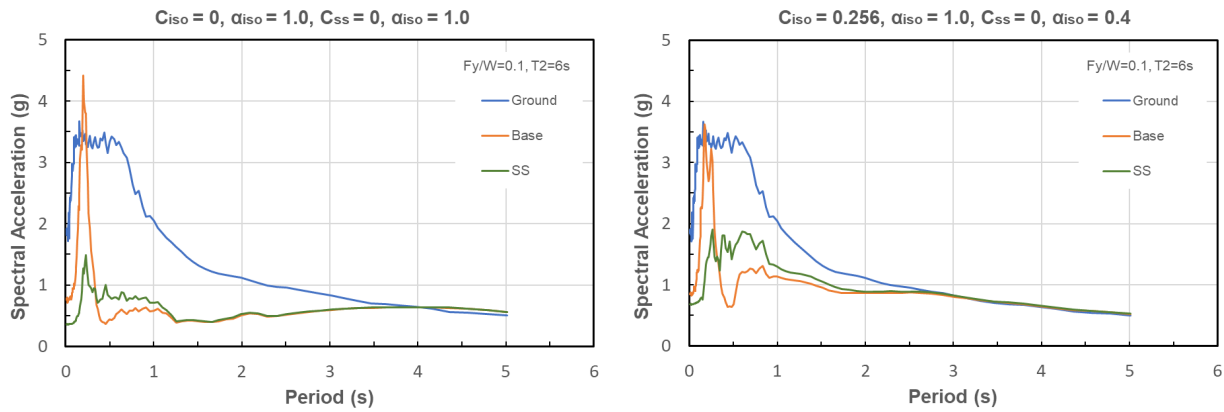


Figure 6. Acceleration response spectra “floor spectra” ($F_y/W = 0.1$ and $T_2 = 6$ s). Left shows isolation only. Right shows isolation including 10% supplementary viscous damping in the isolation layer.

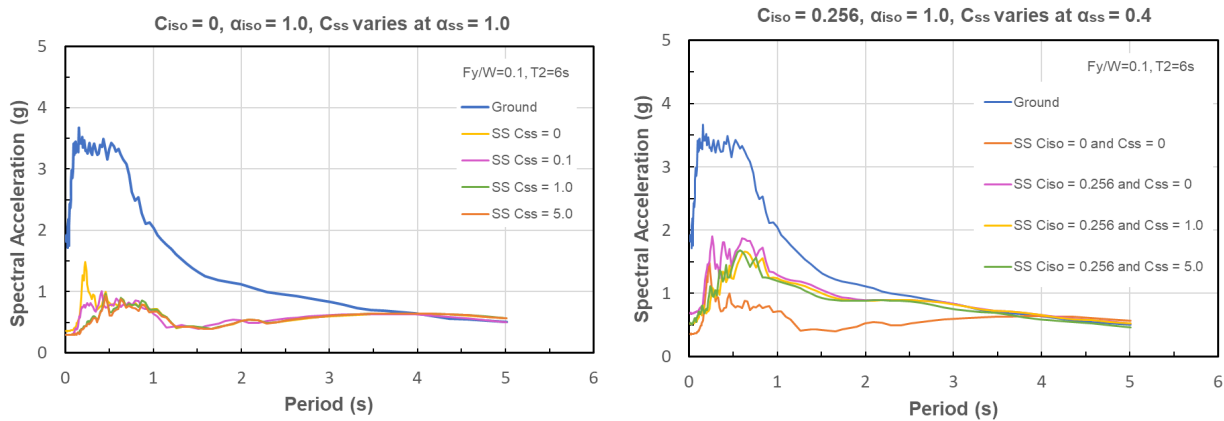


Figure 7. Left: superstructure response spectra “floor spectra” with supplementary viscous damping levels in the superstructure with ($\alpha_{ss} = 1.0$). Right: floor spectra with 10% damping in isolation plus damping added to superstructure ($\alpha_{ss} = 0.4$).

Figure 7 left shows the floor acceleration spectra for a case where viscous damping is added to the superstructure only. There is a reduction in floor acceleration spectra over a wide range of periods from zero up to about 3 seconds. Results were very similar using damping exponents of either 0.4 or 1.0. Figure 7 right shows floor acceleration spectra for the TS 1170.5 demands for an example model with 10% viscous damping in the isolation layer plus additional damping in the superstructure. The analyses indicate that accelerations in the superstructure tend to increase due to the addition of viscous damping in the isolation layer that cannot be neutralised by adding viscous damping in the superstructure.

Finally, a study was carried out to test whether the significantly increased demands of TS 1170.5 over NZS 1170.5 (more than 2 times) could be neutralised using added viscous damping. Table 1 summarises maximum response values for an example isolated building in Wellington ($F_y/W = 0.1$ and $T_2 = 6$ seconds). Maximum response parameters include displacement of the isolation system, drift and absolute acceleration of the superstructure. With the addition of 13% viscous damping to the isolation layer, the displacement demand on the isolation using TS 1170.5 was reduced to the same as NZS 1170.5. With the addition of increasing levels of added viscous damping to the superstructure, the maximum drift for TS 1170.5 could be reduced to match NZS 1170.5, however the peak superstructure acceleration could not be reduced to the

same extent. (matching the conclusion from Figure 7). Increased superstructure acceleration response suggests greater superstructure forces, which may require additional elastic strength to be provided.

Table 1: 2DOF model results for NZS 1170.5 and TS 1170.5 with supplementary viscous damping.

Seismic Input	PGA (g)	Added Damping in Isolation C _{ss} *		Isolation Displ. (m)	SS Drift (%)	SS Max. Acceln (g)
NZS 1170.5 AEP 1/2500	0.97	0%	0.0	0.54	0.40%	0.34
TS 1170.5 AEP 1/2500	1.83	0%	0.0	1.24	0.38%	0.35
TS 1170.5 AEP 1/2500	1.83	13%	0.0	0.55	0.85%	0.74
TS 1170.5 AEP 1/2500	1.83	13%	1.0	0.54	0.30%	0.60
TS 1170.5 AEP 1/2500	1.83	13%	5.0	0.53	0.03%	0.62

* C_{ss} is the damping coefficient for damping added to the superstructure (with exponent $\alpha_{ss} = 0.4$).

6 CONCLUSIONS

The parametric study shows that increased seismicity demands of TS 1170.5 on isolated structures can be largely neutralised by addition of viscous damping in the isolation system and superstructure. Increased displacement demands in the isolation can be controlled with supplemental viscous damping added in parallel with the isolators, however, this causes increased drifts and floor accelerations in the superstructure. The increased superstructure drift demands can be controlled by also adding viscous damping in the superstructure, however, it does not appear possible to neutralise floor acceleration increases. Damping added to the superstructure with a damping exponent of 0.4 were found to be more effective than devices with a damping exponent of 1.0.

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