Effect of Soil Depth on Inelastic Displacement Spectra

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SUMMARY:
In the present paper, effect of soil depth on acceleration spectra, displacement spectra, amplification factors and displacement modification factors have been studied analytically. 1-D ground response analysis has been carried out for the Treasure Island geotechnical array site profile, which represents a soft-soil/rock geological profile, assuming different depths of the bedrock. Spectrum compatible time histories corresponding to NEHRP site class "B" were generated using a wavelet based procedure, corresponding to two level of seismicity, that is, PGA of 0.05g and 0.36 g, at rock outcrop. The effect of soil depth on the shape of response spectra and amplification factors is presented. The analytically obtained displacement modification factors (i.e. ratios of inelastic spectral displacement to elastic spectral displacement) are compared with empirical equations proposed by different researchers. The effect of variation in soil stratum depth for the same site class, is significant on the shape of response spectra and amplification factors; however, the effect on displacement modification factor is negligible.

Keywords: Response Spectra, Amplification Factors, Displacement Spectra, Inelastic Spectra, Displacement Modification Factor

1. INTRODUCTION

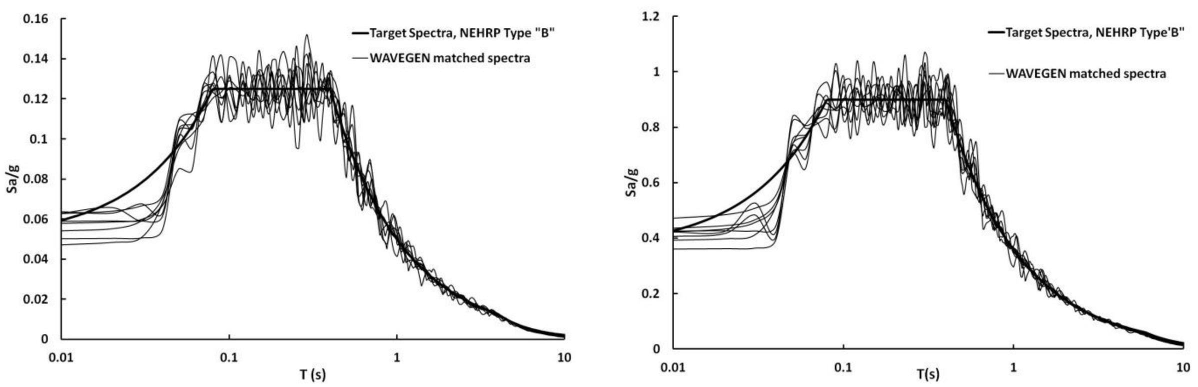
In the past few decades, there is a paradigm shift in seismic design of structures from conventional force based design to displacement based design. Traditionally, the design codes specify the design hazard in terms of elastic acceleration spectra, but inelastic displacement spectrum is the most common and convenient representation of design hazard for displacement based design. Accordingly, a number of methods to obtain inelastic design displacement spectrum from the elastic spectrum, have been developed by different researchers.

The effect of soil in design codes is considered through amplification factors based on soil classification using average shear wave velocity ($V_{s,30}$) in top 30 m strata and the depth of the soil is still not a criterion of classification in most of the national codes. Many researchers have highlighted that the soil classification based on $V_{s,30}$ is not adequate and depth of soil has a predominant effect on the elastic spectra [Pitilakis *et al*., 2004; Park, 2003]. Soil depth also has significant effect on soil amplification [Kamatchi *et al*., 2010]. Some researchers have pointed out that soil strata also has a significant effect on displacement modification factors used to convert elastic spectra to inelastic spectra [Mollaioli and Bruno, 2008; Garcia and Miranda, 2004].

In this study, the Treasure Island site strata has been considered, where the soil profile details are available up to the bedrock. Four other strata were assumed by varying the depth of the bedrock to different levels in the Treasure Island Site strata. Ground response analysis was carried out for the five strata for spectrum compatible time histories, generated using the wavelet based procedure [Mukherjee and Gupta, 2002], for PGA of 0.05g and 0.36g, at NEHRP site class "B" [ASCE, 2006] site class. The ground acceleration and displacement spectra have been plotted and the effect on the shape is studied. The ratio of spectral acceleration on soil surface to the spectral acceleration on the rock outcrop (henceforth referred as "Amplification Factor") has been derived for the two levels of seismicity (that is, PGA of 0.05g and 0.36 g). The Displacement Modification Factors for the five strata were also computed and compared with the available empirical studies.

2. SPECTRUM COMPATIBLE MOTIONS

Earthquake records at rock sites (site class 'B' as per NEHRP classification with average shear wave velocity, $V_{S,30}$ > 750 m/s) for magnitude (M_s) in the range of 5 to 8 were downloaded from the Pacific Earthquake Engineering Research Center (PEER) database [www.peer.berkeley.edu] and scaled in the time domain to the target peak ground acceleration, that is, 0.05g and 0.36 g. The scaled time histories were then made compatible with the NEHRP site class B (rock outcrop) spectrum for the targeted PGA of 0.05 g (corner period of 4 s) and 0.36 g (corner period of 6 s) using spectral matching program WAVEGEN [Mukherjee and Gupta, 2002]. Fig. 2 shows the target and matched response spectra for the two values of PGA. The time histories have been band pass filtered with the lower frequency as 0.1 Hz and upper frequency as 25 Hz and base-line corrected. The corrected spectrum compatible motions were then used as input on rock outcrop in the 1-D wave propagation analysis using DEEPSOIL [Hashash *et al*., 2011].



(a) (b)

FIGURE 2. Earthquake spectra of selected time histories matched to 5% damped elastic design response spectra for PGA equal to (a) 0.05 g and (b) 0.36g at NEHRP site class B.

3. ANALYTICAL STUDY

A series of analyses was performed using DEEPSOIL [Hashash *et al*., 2011], a nonlinear 1-D site response analysis software for deep soils, for the five considered sites as shown in Tables 3.1 to 3.5. The actual Treasure Island geotechnical array profile (Site 4) has been shown in Table 3.4. The total depth of soil (*H*) at the actual site is 88 m with fundamental period of 1.46s. The other sites have been generated by varying depth of bedrock while retaining the soil thickness/impedance variability of the actual profile. For example, in case of Site 3 (Table 3.3), the bedrock is assumed to be at the level of -28 m where the first major impedance contrast occurs. The estimated fundamental period for this site is 0.64 s. In case of Site 2, as shown in Table 3.2, the first stiff layer has been removed, since soft soil layer underneath a stiff soil layer produces less amplification as observed from past studies [Zhao and Zhang, 2008]. This results in a stratum with total depth, *H* equal to 25 m and fundamental period same as for Site 3. Site 1, as shown in Table 3.1, has been considered to take into account the effect of shallow soft layers which has greater amplification potential as compared to deep soils [Zhao and Zhang, 2008] with depth as 11m and fundamental period equal to 0.29 s. Finally in case of Site 5, as shown in Table 3.5, the bottom-most soil layer has been extended to bedrock to consider the effect of very deep soil with depth of 200 m and the fundamental period as 2.63 s. As per NEHRP site classification, all the five sites can be classified as 'D' since $V_{s\,30}$ lies in the range of 180 to 360 m/s.

Table 3.1. Geotechnical profile at Site 1, H = 11 m, $V_{s\ avg}$ = 153 m/s, $V_{s\ 30}$ = 303 m/s

Layer No.	Material	Thickness(m)	Unit Weight (kN/m^3)	Shear Wave Velocity (m/s)
1	Gravelly Sand	5	17	130
2	Sand-fine-sandy loam	6	17	180
3	Bed rock	0	25	700

Table 3.2. Geotechnical profile at Site 2, H = 25 m, $V_{s\ avg}$= 169.5 m/s, $V_{s\ 30}$ = 194 m/s

Layer No.	Material	Thickness(m)	Unit Weight (kN/m^3)	Shear Wave Velocity (m/s)
1	Gravelly Sand	5	17	130
2	Sand-fine-sandy loam	6	17	180
3	Clay (Holocene Bay Mud)	14	16	185
4	Bed rock	0	25	700

Table 3.3. Geotechnical profile at Site 3, H = 28 m, $V_{s\ avg}$= 176 m/s, $V_{s\ 30}$ = 185.3 m/s

Layer No.	Material	Thickness(m)	Unit Weight (kN/m^3)	Shear Wave Velocity (m/s)
1	Gravelly Sand	3	17	260
2	Gravelly Sand	5	17	130
3	Sand-fine-sandy loam	6	17	180
4	Clay (Holocene Bay Mud)	14	16	185
5	Bed rock	0	25	700

Table 3.4. Geotechnical profile at Site 4, H= 88 m, $V_{s\ avg}$= 241.8 m/s, $V_{s\ 30}$= 181.5m/s

Layer No.	Material	Thickness(m)	Unit Weight (kN/m^3)	Shear Wave Velocity (m/s)
1	Gravelly Sand	3	17	260
2	Gravelly Sand	5	17	130
3	Sand-fine-sandy loam	6	17	180
4	Clay (Holocene Bay Mud)	14	16	185
5	Sandy loam	14	16	320
6	Sandy Clay	33	16.5	260
7	Gravelly Sand	6.5	18	380
8	Sandy Clay	6.5	16.5	380
9	Bed rock	0	25	700

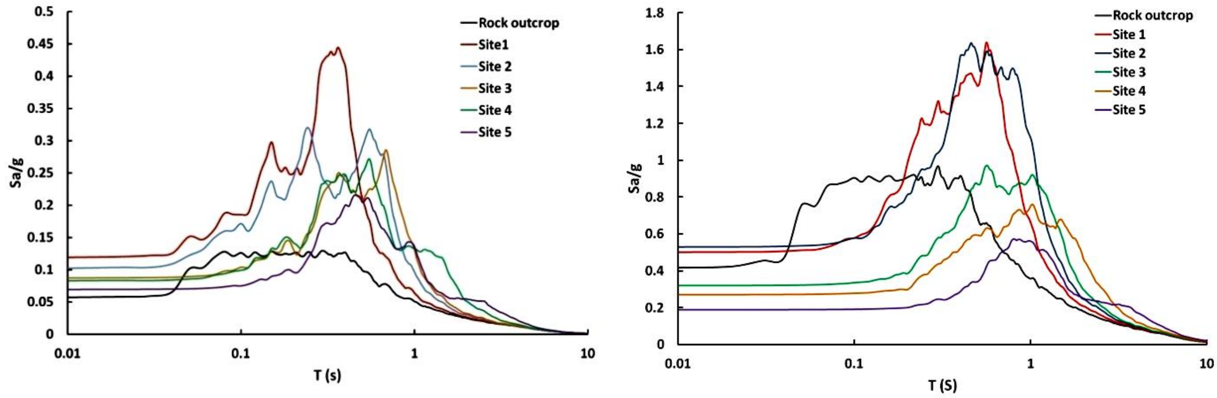
Table 3.5. Geotechnical profile at Site 5, H= 200 m, $V_{s\ avg}$= 303.6 m/s, $V_{s\ 30}$= 181.5 m/s

Layer No.	Material	Thickness(m)	Unit Weight (kN/m^3)	Shear Wave Velocity (m/s)
1	Gravelly Sand	3	17	260
2	Gravelly Sand	5	17	130
3	Sand-fine-sandy loam	6	17	180
4	Clay (Holocene Bay Mud)	14	16	185
5	Sandy loam	14	16	320
6	Sandy Clay	33	16.5	260
7	Gravelly Sand	6.5	18	380
8	Sandy Clay	118.5	16.5	380
9	Bed rock	0	25	700

The nonlinear behaviour of soil was modelled using reduction in elastic modulus and equivalent damping. In the present study, the modulus reduction curves and equivalent damping ratios proposed by Seed *et al*. [1970, 1986], Sun *et al*. [1988] and Ishibashi-Zhang [1993] were used for different soil types. The mean response of each site was obtained for the eight input time histories corresponding to each value of PGA.

4. RESPONSE SPECTRA

Figure 4.1 shows the mean elastic acceleration spectra for different sites along with rock outcrop for 5% damping. As can be seen from Fig. 4.1(a), the spectral accelerations vary for the different sites both in the short period as well as in long period range. Site 1 (the shallowest stratum) has the highest spectral acceleration value whereas Site 5 (the deepest stratum) has the least value.

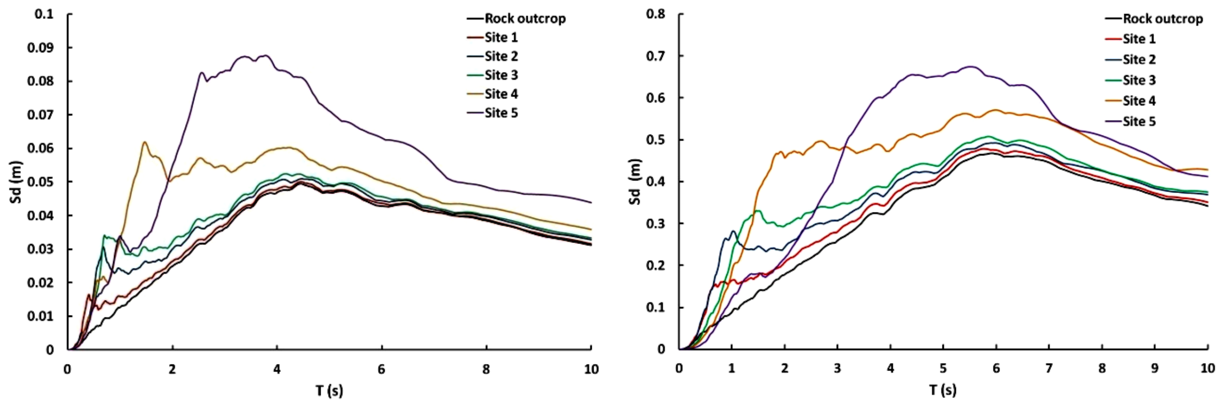


(a) (b)

FIGURE 4.1. 5% damped mean elastic acceleration response spectra for different sites for PGA equal to (a) 0.05 g and (b) 0.36g.

It can be observed from Fig. 4.1(b) that with the increase in soil depth, there is a gradual decrease in the value of spectral acceleration, except for the first two sites. Although the fundamental period of Site 2 and Site 3 are the same, the difference in the shape of their spectra is significant unlike in Fig. 4.1(a).

Figure 4.2 shows the mean elastic displacement spectra for the five sites along with rock outcrop for 5 % damping ratio. The fundamental period of the site has effect significant enough to change the shape of the displacement spectrum, and the effect increases with the depth of soil. As can be seen in the Figures, the long period corner periods (between velocity controlled and displacement controlled ranges) are quite different for different sites and increase with increase in depth of soil column. In case of Sites 1, 2 and 3, subjected to 0.05 g PGA at rock outcrop, the spectral displacement still increases till 4 s (corner period in case of rock outcrop) but in case of Sites 4 and 5, spectral displacement becomes constant or starts descending at much lower periods. Similar observation is also made in case of higher PGA (0.36 g) in Fig. 4.2 (b).



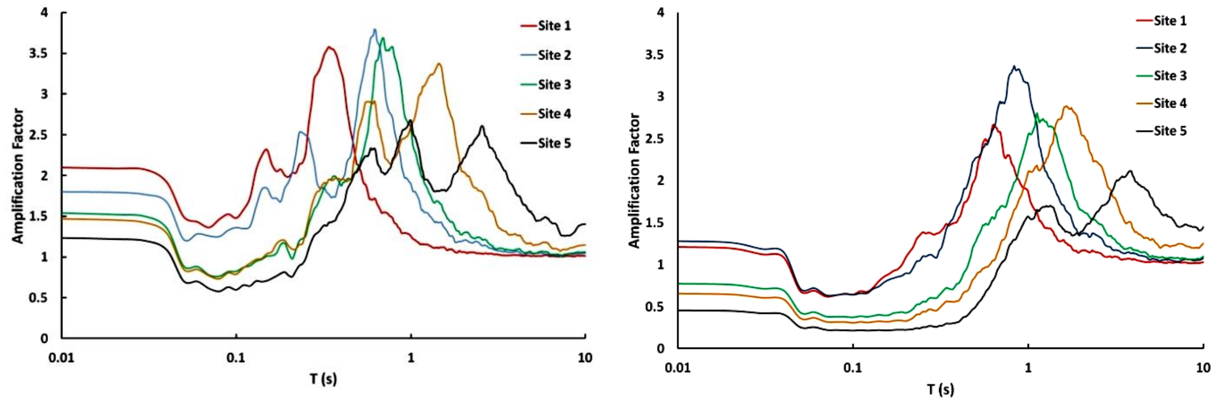
(a) (b)

FIGURE 4.2. 5% damped mean elastic displacement response spectra for different sites for PGA equal to (a) 0.05 g and (b) 0.36g.

The inelastic displacement spectra for the five sites for the two values of PGA were also obtained for different ductility levels (μ=2, 4 and 6). The spectra are been shown here, but the same have been used to compute Displacement Modification Factors.

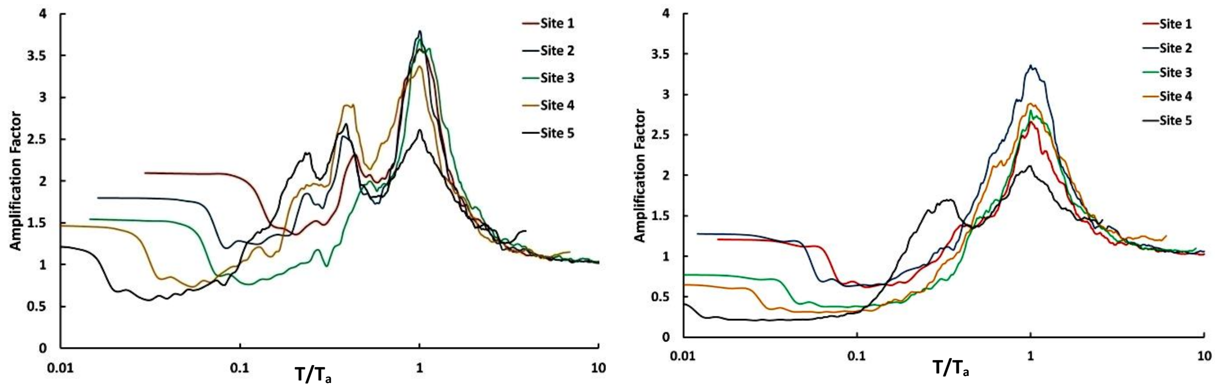
5. AMPLIFICATION FACTORS

Amplification factors (ratio of spectral ordinates at soil surface to those at rock outcrop) were also derived for the two levels of seismicity as shown in Fig. 5.1 and 5.2. Figure 5.1 (a) shows that for the low PGA (=0.0.5 g) the peak amplification factor for all the sites, considered herein, is around 3.5 and the peaks occur near the fundamental periods of the sites, except for the deepest soil site (Site 5), for which a smaller amplification factor is observed. Since the variation of amplification factors for Site 3 and Site 4 are almost identical, despite the soil depth being quite different, it can be concluded that the peak amplification factor is governed to a large extent by the first major impedance contrast (as observed in past studies by Zhao, 2011; and Dobry and Iai, 2001). Further, for higher PGA (0.36g as shown in Fig. 5.1(b)) it was observed that the amplification factor for Site 2 is higher as compared to Site 3, although the fundamental periods of the two sites were equal. This can be attributed to lower amplification in case of soft soil layers underlying stiff layers as reported by Zhao and Zhang (2008).



(a) (b)

FIGURE 5.1. Analytically obtained mean amplification factors for different sites for PGA equal to (a) 0.05 g and (b) 0.36g.



(a) (b)

FIGURE 5.2. Analytically obtained mean amplification factors for different sites for PGA equal to (a) 0.05 g and (b) 0.36g, plotted against normalized period.

To highlight the effect of site period, the amplification factors are also plotted against normalized period, T/T_a as shown in Fig. 5.2, where T_a is the predominant period of the ground motion, which in this investigation is approximated by the period corresponding to the peak of the respective elastic acceleration spectrum. It is noted that variation of amplification factor takes a simpler form when plotted against normalized period, as expected on the basis of past studies (Gazetas, 2006). When plotted in the normalized form, the average amplification factor exhibits a characteristic peak at value of T/T_a close to 1. It is also interesting to note that the amplification factors, for all the sites, are quite close at normalised period equal to unity and almost coincide at larger normalised period. The effect of depth on amplification factors is observed only in the short period range ($T<T_a$) where the dependence of the amplification factors on period and PGA is also clearly visible.

6. DISPLACEMENT MODIFICATION FACTORS

The displacement modification factor C_μ is defined as the ratio of the ordinate of the inelastic displacement spectrum to the elastic value for a given period. Mathematically it is expressed as

$$C_\mu(T) = \frac{S_{d(inelastic)}}{S_{d(elastic)}} = \mu\frac{S_{d(yield)}}{S_{d(elastic)}} \tag{6.1}$$

The displacement modification factors C_μ were computed for the five sites, for three different constant ductility levels (2, 4 and 6) and 5% initial damping. Elastic-perfectly plastic hysteretic behaviour has been assumed in the study.

Empirical expressions for C_μ have been derived by Miranda (2000), Deccanini *et al*., (2003), Mollaioli and Bruno [2008] and other researchers using statistical studies on inelastic displacement ratios of different site classes. The obtained empirical equation has the following form:

$$C_\mu = [1 + \left(\frac{1}{\mu} - 1\right) e^{(-C1\,T\,\mu^{-C2})}]^{-1} \tag{6.2}$$

where, the coefficients C_1 and C_2 are defined as functions of the displacement ductility ratio, μ, and of the soil conditions as shown in Table 6. For site class D, the coefficients provided by Miranda and Deccanini *et al*. are identical. As seen in Fig. 6, the analytical results for a given ductility overlap for different sites and match quite well with the empirical results by Miranda (2000) and Deccanini *et al*., (2003). Therefore, the effect of soil depth on displacement modification factors appears to be insignificant.

Table 6. Coefficients C_1 and C_2 for site class D as per different researchers

Researcher	**μ**	**Soil**	**C_1**	**C_2**
Miranda (2000)	2, 4, 6	D	12	0.8
Deccanini *et al*., (2003)	2, 4, 6	S2 (intermediate soil)	12	0.8
Mollaioli and Bruno (2008)	2, 4, 6	D	6	0.8

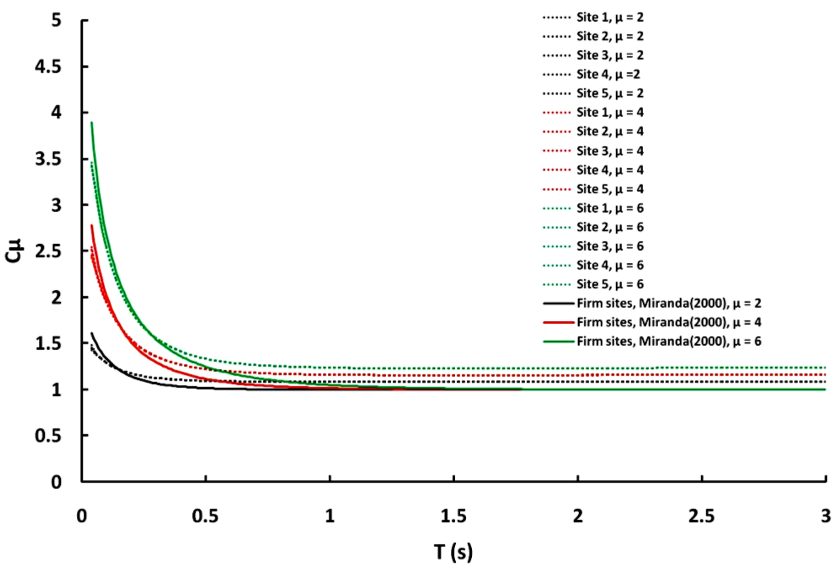


FIGURE 6. Comparison of analytically obtained mean displacement modification factors with empirical results.

7. CONCLUSIONS

Following conclusions can be drawn from the analytical study performed in the present paper:

1. Soil depth affects the shape of response spectra significantly, affecting the long period corner period which is governed by the predominant site period.
2. The first major impedance contrast governs the peak soil amplification factor to a large extent. However, for very deep soils (Site 5, having 200 m deep stratum) the peak amplification factor is reduced. The effect of depth on amplification factors is observed only in the short period range ($T<T_a$) where the dependence of the amplification factors on period and PGA is also clearly visible.
3. Shallow soft layers have more amplification potential for ground acceleration, than very deep soil layers, as the amplification factor gradually reduces with depth. However, the effect of depth of soil strata on displacement spectrum is drastically different due to change in corner period. The peak displacement for deep soils is much larger, having significant consequences in the context of displacement based design.
4. Displacement Modification Factor C_μ is observed to be insensitive to the depth of the soil stratum.

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