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Seismic site classification practice in Australia, China and India: suitability

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SEISMIC SITE CLASSIFICATION PRACTICE IN AUSTRALIA, CHINA AND INDIA: SUITABILITY

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Abstract—Seismic site classifications are widely used to represent seismic site effects and estimate the hazard parameters at soil surface. Most countries including Australia, China and India follow seismic site classification system similar to that in International Building Code (IBC), which is based on 30 m average shear wave velocity (SWV), Standard Penetration Test (SPT) N values and undrained shear strength. The site classification system in IBC is developed based on the studies carried out in United States. The present paper presents the seismic site classification according to IBC considering 30 m average SWV and SPT N and compares with seismic site classification given in the seismic design codes of Australia, China and India. SWV and SPT N values have been collected from different part of Australia, China and India. These data were selected considering rock depth; the data are available for depth of few meters to about 180 m. This study shows that site classification based on 30 m depth gives stiffer site class and lower spectral acceleration coefficient for building design. New site classification based on average soil thickness, SWV and SPT N up to engineering rock has been proposed. The proposed site classification represents soil thickness and shear stiffness of site rather than adding the rock SWV and SPT N values, if the depth of soil is less than 30 m or omitting the same if the depth of engineering rock is greater than 30m.

INTRODUCTION

The widespread destruction caused by many earthquakes particularly Guerrero earthquake (1985) in Mexico city, Spitak earthquake (1988) in Leninakan, Loma Prieta earthquake (1989) in San Francisco Bay area, Kobe earthquake (1995), Kocaeli earthquake (1999) in Adapazari are important examples of site-specific amplification of ground motion, even at locations far away (100-300 km) from the epicenter (Ansal, 2004). The recent 2001 Gujarat-Bhuj earthquake in India is another example, with notable damage at a distance of 250 km from the epicenter. In the twentieth century an average of about 17000 people per year were killed in natural disasters (Chen and Scawthorn, 2003; Walling and Mohanty, 2009). More than 50% of the casualties were inflicted by earthquakes, among all the natural disasters faced by human being in the twentieth century (leaving out the fatalities caused by drought and famine). Most of these casualties can be seen in the region of Asia-Pacific with the deaths amounting to more than 85% of the total casualties (Walling and Mohanty, 2009). It is now widely accepted that one of the major causes of earthquake destruction is due to local site effect (amplification of ground motion due to local subsoil conditions). Soil condition modifies ground motion and in many cases result in greater amplitude, which also modifies frequency content and duration of ground motion. Site-specific ground response analysis aims to determining the effect of local soil conditions, i.e. amplification of seismic waves. Hence estimating the earthquake response spectra with proper consideration of site effects is very important for designing new structures and assessment of existing structures (Anbazhagan and Sitharam, 2008a and b).

The response at the surface of soil deposit is dependent on the frequency of the motion in bedrock, the geometry and material properties of the soil layers above the bedrock. These parameters are directly or indirectly quantified and represented by many researchers as part of the seismic microzonation study. Seismic site characterization is widely followed to quantify soil amplification or site effects. Although many methods are being recommended in design codes worldwide, most popular are those that consider borelogs with standard penetration test (SPT) N values and shear wave velocity from Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW) (Anbazhagan, 2009). Most of these studies consider the top 30 m average of SPT N values or SWV for site classification. These site classification schemes are combined with probabilistic approach to estimate the surface level hazard accelerations (Raghu Kanth and Iyengar, 2007; Anbazhagan et al, 2009a). Even though soil amplification is well correlated with the top 30 m SWV values, these site classification schemes are still under significant attention (Marek et al., 2001). In this study, a suite of SPT N and SWV data are collected from Austraila, China and India, which are classified according to 30 m average seismic site classification given in National Earthquake Hazards Reduction Program (NEHRP) (BSSC, 2001) and International Building Code (IBC, 2006). This study reveals that using 30 m average without considering rock depth may lead to stiffer site class for sites having engineering depth less than 25 m and softer site class for sites having engineering depth greater than 35 m. A new classification scheme has been proposed considering soil thickness and stiffness rather than 30 m averages.

GEOTECHNICAL DATA

The effects of local soil condition are directly related to significant damage and loss of lives in an event of earthquake. This has been demonstrated in many past earthquakes and has been widely accepted (Anbazhagan and Sitharam, 2008a; 2009a and b). Even moderate earthquakes may cause severe damage to buildings and even loss of lives if ground motion is amplified significantly by local soil deposits. Newcastle earthquake (1989) in Australia is one of many examples where significant damage and deaths were observed due to local site effects where earthquake magnitude was only 5.6 (Institute of Engg, 1990). The correlation between site effects and building damages was studied by many researchers. Figure 1a shows the damage intensity versus depth of soil (after Seed et al., 1972). Figure 1b shows the correlation between ratios of shear wave velocity of soil to rock with amplification magnitudes (after Shima, 1978). Geotechnical properties of local soils play a major role in site amplification. Many seismic microzonation studies are started with subsurface geotechnical modelling and database (Sitharam and Anbazhagan, 2008 and 2009). Even though seismic microzonation study for major Australian cities was carried out but only limited consideration of geotechnical subsurface model aspects is given for site response study.

Literature shows that seismic site classification for seismic microzonation studies are mainly based on NEHRP and IBC recommendations. In these regions where engineering rock depth varies from few meter to several hundred of meters, adopting 30 m average may result in erroneous site classification and thus the design response spectrum. In order to highlight these aspects, in this study, site-specific geotechnical data of soil types and stiffness (in the form of SPT N or SWV) with depth up to rock were gathered and compiled from published literatures. These data contain drilled boreholes with SPT N values and SWV profiles. The SWV of 330 m/s and 700 m/s plus or minus 10% and SPT N value of 50 or rebound for 5 mm penetration and 100 for no penetration are considered as weathered rock and engineering rock as per Anbazhagan and Sitharam (2009a).

SEISMIC SITE CHARACTERIZATION

Many researchers reported that local site conditions could play a dominant role in damage distribution as well as in the recorded strong ground motion (Roca et al., 2006). Geotechnical characteristics of soil deposits play an important role in the level of ground shaking or local site effects. Ground classification of individual sites based on soil boring or SWV is a more direct indicator of local site effects. Site effects in terms of amplification at soil sites require knowledge of shear stiffness of the soil column, expressed in terms of SWV (Borcherdt, 1994). The site classes are defined in terms of SWV up to a depth of 30 m, denoted by Vs^{30}, if no measurements of SWV to 30 m are feasible, standard penetration resistance (N_{30}) and undrained shear strength (S_u^{30}) could be used (Borcherdt, 1994). SWV can be directly measured in field tests or it can be estimated from existing correlations between SPT blow-counts (SPT-N) and SWV (Hasancebi and Ulusay, 2006). A number of correlations are available between SPT N and SWV; suitable correlation can be used based on the soil type.

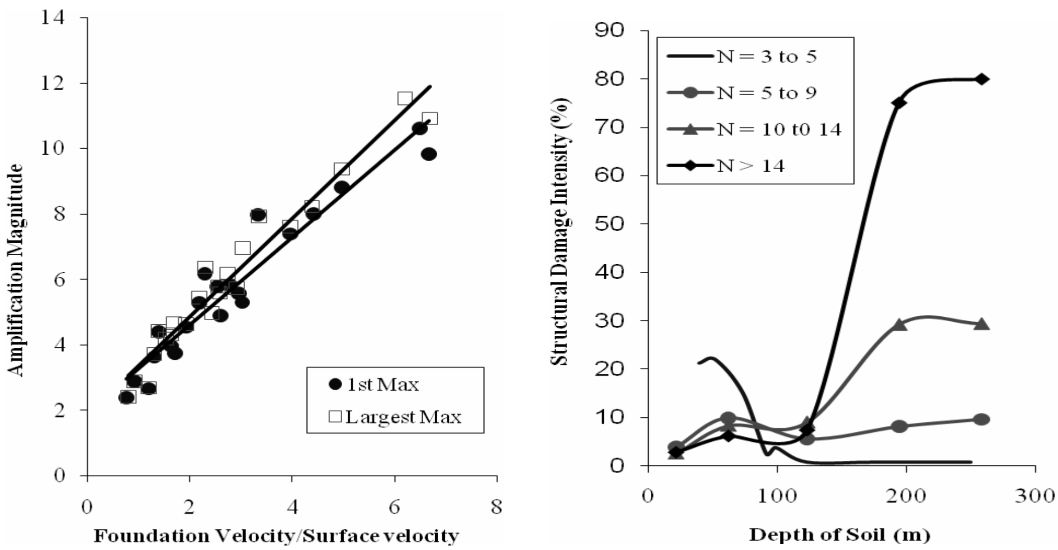

Figure 1a and b: Stiffness and Depth Directly Related to Damage of Structures

Seismic ground response characteristics, defined generally as "site effects", are inevitably incorporated in modern seismic code provisions in many countries. The details of consideration are not fully consistent. Table 1 shows the summary of site classes adopted in National Earthquake Hazards Reduction Program (NEHRP) (BSSC, 2001), International Building Code (IBC, 2006) or Uniform Building Code (UBC, 1997), Australian Standards Part 4: Earthquake Actions in Australia (AS 1170.4, 2007), China Code for Seismic Design of Building (GB 50011, 2001) and Indian Code (BIS 1893, 2002). In order to avoid confusion of detailed specification, only key and common information is given in Table 1 for direct comparison. The soil types are mainly accounted by average SWV or SPT N values. In this study, the site classification using SPT N and SWV are considered. Undrained shear strength (S_u) is omitted as these are not available in all codes. The equivalent shear stiffness values of soil based on SPT N or SWV over 30 m depth can be calculated by

$$N_{30}\,or\,Vs^{30} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n}\left(\frac{d_i}{N_i\,or\,Vs_i}\right)} \quad (1)$$

where $\sum_{i=1}^{n} d_i$ is summation of total depth, for 30 m average $\sum_{i=1}^{n} d_i$ = 30m, di and Vsi/Ni denote the thickness (in meters) and corresponding shear wave velocity/standard penetration resistance not to exceed 100 blows/0.3m as directly measured in the field without corrections of the ith formation or layer respectively, in a total of n layers, existing in the top 30 m. Table 1 shows the site classification according to 30m SWV or N by NEHRP and IBC. From Table 1, site classification of IBC2006/UBC1997 and NEHRP are almost identical, which consider five main categories and one special condition (Site Class F) for very loose soil where detailed site specific study is necessary. Australian Standard recommends five methods to classify a site, site class based on geotechnical details are placed higher order. General site classification of Australian Standard based SWV and SPT N values are given in Table 1. A detailed site classification procedure for construction site in Chinese Code GB 50011 (2001) was described in Chapter 4, Section 4.1.6. This chapter also includes provision for fault within the site and liquefiable soil. Site classifications are based on 20 m equivalent SWV of soil (Vs20) and thickness of site overlying layers. Site classification according to the Chinese code based on the description of subsurface materials is given in Table 1. There is no separate section for site classification that considers geotechnical characteristics of sites in the Indian code BIS 1893 (2002). But Section 6.3.5.2 describes rough consideration of site conditions by specifying SPT N values and type of foundation. Site classification in Indian code BIS 1893 (2002) are based on SPT N values and given in Table 1. In order to understand difference between site classification schemes in IBC/NEHRP and other seismic codes in the Asia-Pacific region, site classification based on SPT and SWV data collected in the Asia-Pacific region has been presented below.

SITE CLASSIFICATION USING SPT DATA

Boreholes with SPT N values are one of the oldest, popular and common in situ tests used for soil exploration in soil mechanics and foundation engineering. This is being popularly used worldwide in geotechnical projects, because of simplicity of the equipment and easiness of test procedure. In particular SPT tests are widely used for seismic site characterization, site response and liquefaction studies towards seismic microzonation due to large data availability. However these SPT N values may vary even for identical soil conditions because of the high sensitivity to operator techniques, equipment, malfunctions and poor boring practice. So the SPT N values may be used for projects in preliminary stage or where there is a financial limitation. For important project, it is preferable to measure dynamic properties directly by MASW field tests (Anbazhagan and Sitharam, 2009b). SPT is carried out in a borehole, by driving a standard ‘split spoon’ sampler using repeated blows of a 63.5 kg hammer falling through 762 mm. The hammer is operated at the top of the borehole, and is connected to the split spoon sampler by rods. The split spoon sampler is lowered to the bottom of the hole, and is then driven a distance of 450 mm in three 150 mm intervals and the blows are counted for each 150 mm penetration. The penetration resistance (N) is the number of blows required to drive the split spoon for the last 300 mm of penetration. The penetration resistance during the first 150 mm of penetration is ignored, because the soil is considered to have been disturbed (Anbazhagan and Sitharam, 2009b). In present study, SPT N values of the selected soil profiles have been collected from Australia, China and India from Institute of Engg, (1990); Pappin et al., (2008); Anbazhagan and Sitharam (2009a); and Anbazhagan (2004). In total, nineteen boreholes data with SPT N values are used, summary of theses data are given in Table 2.

Equivalent SPT N values for 30 m depth were estimated using equation (1) and presented in Figure 2. SPT N values have been directly used to classify the sites according to IBC/NEHRP; shallow depth data fall in site class C. According to IBC2006/NEHRP, all N30 values above 50 are grouped in site class C. No N30 based criterion is given for site classes A and B, which means N30 of 55, 70, and 85 belong to site class C, but it is not the case. Australian Standard does not have SPT N based site classification for all site classes. SPT N values are used to define site classes D and E (see Table 1), which are insufficient to classify the sites based on SPT N values. Chinese Code recommends measuring SWV for site classification. So no SPT N value based site classification is recommended, however for building categories C or D (and for buildings less than ten stories and not more than 30 m in height), appropriate SWV are permitted as estimate using known geologic conditions. Indian Code suggests three site classes based on SPT N values (not equivalent to 30 m N values), which is too simple and incapable to account for the site effects when compared to other codes. Classifying sites in three categories by only considering SPT N values may not be appropriate to account for site effects.

Table 1: Seismic Site Classification of Asia Pacific Standard with International Standard

Site Class	Generalized soil Description	NEHRP (BSSC,2001)		IBC 2006/ UBC1997		Australian Standards AS 1170.4, 2007		Chinese seismic Code GB 50011(2001)		Indian Standards BIS 1893 (2002)	
		N_{30}	Vs^{30}	N_{30}	Vs^{30}	N_{30}	Vs^{30}	N	Vs^{20}	N	Vs^{30}
A	Hard Rock	N/A	>1500	N/A	>1524	*	>1500	*	*	*	*
B	Rock	N/A	760-1500	N/A	762-1524	*	>360	*	>500	*	*
C	Very Dense Soil and Soft Rock	> 50	360-760	> 50	366-762	*	≤0.6s (surface to rock)	*	250-500	>30	*
D	Dense To Medium Soils	15-50	180-360	15-50	183-366	Soil with SPT N values of <6 for depth of <10m	>0.6s (surface to rock)	*	140-250	All the soil 10 to 30 or Sand with little fines N>15	*
E	Medium To Soft Soil	< 15	< 180	< 15	< 183	Soil with SPT N values of <6 for depth of >10m	More than 10m depth of Soil with Vs ≤150 or less	*	<140	<10	*

*N/A-Not applicable, * Not available, Vs^{30} and Vs^{20} are in m/s*

Table 2: Summary of the Selected Soil Profiles

Country	Data Type	Number	Depth (m)	General Soil Description
Australia	SPT N	3	6–17	Sand, silty sand, silty clay up to rock
	SWV	5	97–180	Sand, silty sand, silty clay up to rock
China	SPT N	1	47	Sand, clay, silty clay and debris flow
	SWV	9	16–96	Sand, clay, silty clay and debris flow
India	SPT N	15	6–30	Red soil, sand, clay and rock
	SWV	15	10–140	Red soil, sand, clay and rock

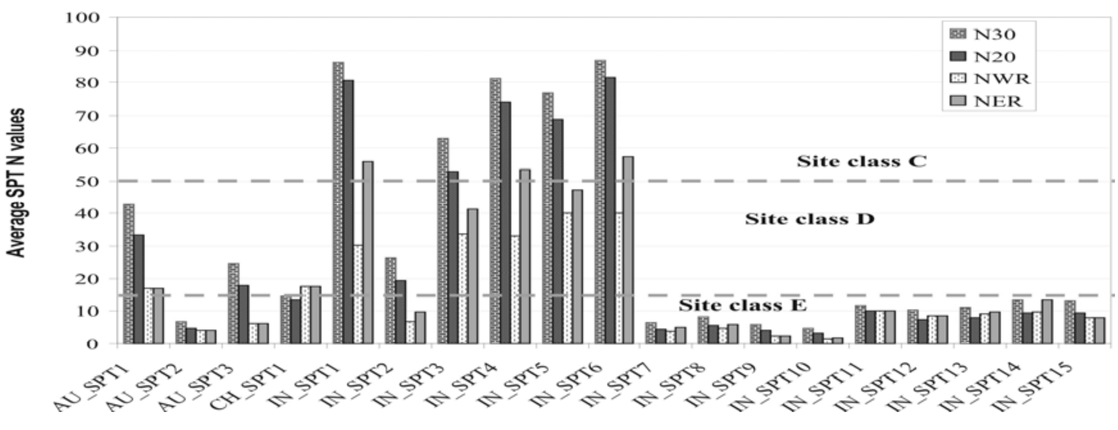

Figure 2: Average SPT N Values of Sites in Asia-pacific Region with Site Classification According to IBC2006/NEHRP

SITE CLASSIFICATION USING SWV DATA

SWV of subsurface is being used by many researchers for seismic site classifications, site response and microzonation study. A number of seismic methods have been proposed for near-surface characterization and measurement of SWV using a great variety of testing configurations, processing techniques, and inversion algorithms. The most widely used techniques are Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW). The SASW method has been used for subsurface investigation for several decades (e.g., Nazarian et al., 1983; Al-Hunaidi, 1992; Stokoe et al., 1994; Tokimatsu, 1995; Ganji et al., 1997). In SASW method, the spectral analysis is performed for a surface wave generated by an impulsive source and recorded by a pair of receivers. MASW is an improved technique by incorporating a multichannel analysis of surface waves using active sources (Park et al., 1999; Xi et al., 1999; Xu et al., 2006; Anbazhagan and Sitharam, 2008c). The MASW has been found to be a more efficient method for unravelling the shallow subsurface properties (Park et al., 1999; Xia et al., 1999; Zhang et al., 2004; Anbazhagan and Sitharam 2008c). MASW is increasingly being applied to earthquake geotechnical engineering for seismic microzonation and site response studies (Anbazhagan and Sitharam, 2008a; 2008b; Sitharam and Anbazhagan 2008 and 2009; Anbazhagan et al., 2009a;). In particular, MASW is used in geotechnical engineering for the measurement of SWV and other dynamic properties (Sitharam and Anbazhagan, 2008b), identification of subsurface material boundaries and spatial variations of SWV (Anbazhagan and Sitharam, 2009a). Recently this seismic refraction method is being used in Australia by the University of Wollongong to identify and measure the type and degree of fouling considering shear modulus variation (Anbazhagan et al., 2009b). Until now, not much refraction studies were carried out in Australia to measure shear properties of subsurface layers except that reported in Collins et al. (2006). Authors highlighted the paucity of near-surface SWV data in Australia and the difficulties in estimating amplification effects. Recently Geosciences Australia initiated SWV measurement using site-specific Spatial Autocorrelation (SPAC) surveys using microtremor (Asten and Roberts, 2005) and seismic cone penetrometer testing in two major cities in Australia (Newcastle and Perth). SWV profiles of Australia were compiled from Collins et al. (2006) and other sources. Similarly SWV profiles of China were collected from Song et al. (2007) and Huang et al. (2004). For India the SWV profiles were complied from Anbazhagan (2007), Boominathan (2004), Boominathan et al (2008), Uma Maheswari (2008a and 2008b). Summary of these data are presented in Table 2.

Equivalent SWV values for depth of 30m and 20m were estimated using equation 1 and presented in Figure 3. Figure 3 shows that 76% of sites are classified as site class D, 5% are site class E and Australian sites 1 and 2 are site classes A and B, respectively, according to IBC2006/NEHRP. Site classification definition in Australian Standard (AS) is similar to IBC/NEHRP recommendation for site class A.

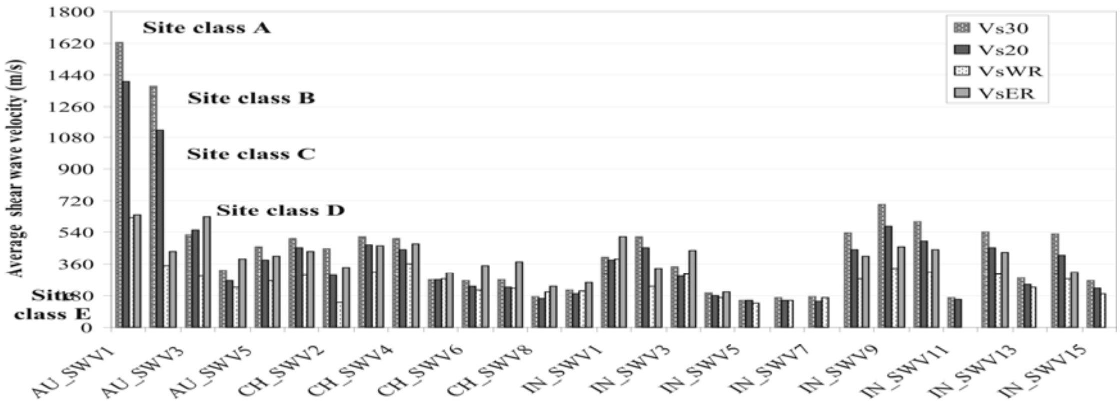

Figure 3: Average SWV Values of Sites in Asia-pacific Region with Site Classification According to IBC2006/NEHRP

But for site class B, AS recommends SWV of greater than 360m/s, which corresponds to site class C in IBC/NEHRP. AS recommends low-amplitude natural site period as criteria for site classes C and D, which is not compatible with IBC/NEHRP recommendation. AS recommends SWV less than 150m/s, which is lower than IBC/NEHRP recommendation. Chinese code categories sites into four classes based on 20 m average SWV and thickness of overlying soil deposits. The range of values specified in Table 4.1.6 in Chinese Code is much lower than those in IBC/NEHRP. No SWV based site classifications are given in the Indian Code.

NEW SITE CLASSIFICATION

Countries in the Asia-pacific region have been severely affected by past earthquakes, but earthquake standards of these countries (including Australia, China and India as considered in this study) do not have adequate provision to account for site effects. Site classification studies for seismic microzonation in these countries are based on the top 30 m soil stiffness similar to IBC2006/UBC1997 and NEHRP using SPT data and measured SWV. IBC2006/UBC1997 and NEHRP site classification are developed based on studies conducted in the United States, which may not be directly applicable in other parts of the world. IBC2006/UBC1997 and NEHRP classify all the sites having N30>50 as site class C, which is not applicable for all the sites (Anbazhagan 2009). Anbazhagan (2009) highlighted that considering 30 m average criteria for sites having rock depth of less than 30 m (1 to 25 m) and that exceeding 30 m may not be accurately represented by the corresponding site class. In this study, new average of SPT N and SWV up to weathered rock or engineering rock has been proposed. This study shows that average 30 m and 20 m concept without considering rock depth gives larger SPT N and SWV values (stiffer site classes) for shallow rock depth and lesser SPT N and SWV values (softer site classes) for deep rock depth. Equivalent value up to weathered rock is always lower than that equivalent up to engineering rock (see Figure 3). This study shows that equivalent values of SPT N or SWV up to engineering rock are more representative of site class, as the amplifications are negligible in rock (SWV>700m/s). The proposed site classification matches with 30 m site classification for sites with engineering rock at depth of 25 m to 35 m. These studies are based on equivalent value calculations; this has to be verified using site response studies.

SUMMARY

This paper highlights the site effects consideration in seismic design standards in Asia-Pacific countries including Australia, China and India. Standards in these countries do not have adequate provision to account for site effects when comparing to IBC2006/UBC1997 and NEHRP recommendation. Direct adoption of IBC2006/UBC1997 and NEHRP classifications for sites having shallow engineering rock in Asia-Pacific region may result in stiffer site class. Considering equivalent SPT N or SWV up to engineering rock provides better representation of site effects.

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