Interpretation of CPTU tests carried out in lacustrine soft clay, Mexico City

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Abstract: The use of the piezocone test (CPTU) for geotechnical site investigation offers direct field measurements of geostratigraphy and soil characterization. Its execution time is much less in comparison with the conventional drilling, sampling and instrumentation procedures commonly used in Mexico and offers a great opportunity to accelerate the field work for important geotechnical projects, thus reducing costs. Recently, this kind of test was used in a broadly explored area in the soft lacustrine deposits of Mexico City Valley. In this paper, geotechnical parameters obtained from CPTU and dissipation tests are evaluated for the lacustrine clays of this area, using methods based on cavity expansion theory (CE) and critical state (CS), and compared with the results of laboratory tests and field instrumentation.

Résumé: L'investigation géotechnique de terrain au moyen de l'essai effectué par piézocône (CPTU) offre la connaissance de la stratigraphie du site aussi bien que la caractérisation du sol. Le temps de réalisation de l'essai est beaucoup moins que les essais conventionnels de forage, relevage des échantillons, essais de laboratoire et instrumentation, utilisés en Mexique. Ceci permet d'accélérer l'exploration nécessaire pour obtenir les paramètres de conception des grands ouvrages tout en réduisant significativement les coûts. Récemment on a utilisé l'essai par piézocône dans une surface très exploré des dépôts lacustres du val de la ville de Mexico, et dans cette article est présenté l'évaluation des paramètres géotechniques pour les argiles lacustres obtenus au moyen de l'essai CPTU et essais de dissipation, en utilisant les théories de l'expansion des cavités (CE) et de l'état critique (CS), vis à vis des résultats de laboratoire et de mesures avec la instrumentation géotechnique installée dans le site.

Keywords: compressibility, hydraulic conductivity, in situ tests, permeability, water table.

INTRODUCTION

The geotechnical design of all civil work requires the appropriate determination of the soil shear strength resistance, deformability and compressibility, together with the definition of the hydraulic conditions of the different soil strata involved in the design. The importance of being able to obtain these values with the best precision in the shortest time possible is of great importance in the duration and economy of the civil engineering projects.

During the geotechnical investigation, the determination of the soil hydraulic conditions is based on different techniques such as recording the water level inside the borehole until the installation of different instruments such as: open, electric or pneumatic piezometers. The response time of those instruments depends on the permeability of soil and the procedure executed in its installation, obtaining reliable results after several days. The piezocone is a tool that allows the geotechnical engineer to estimate the resistance and compressibility parameters of the explored materials as well as to determine the soil hydraulic conditions in a relatively short time through the execution of dissipation tests.

REGIONAL GEOLOGY

The lacustrine soil deposits of the Mexico Valley owe their origin to the formation of six great lakes: Ecatepec, Zumpango, Texcoco, Mexico, Xochimilco and Chalco, after the then Sierra Chichinautzin closed the watershed of Mexico during the Quaternary Superior (Castillo, M.R., 1978), in addition to the sediments carried by the tributaries which flowed into the watershed. These deposits are characterized by very high water content; high plasticity, high compressibility and low shear strength clays. Of particular interest are the lacustrine soils in the north zone of the former Chalco Lake, as these are primarily formed by high plasticity silts and clays with insertions of ash and silty sand, as well as layers with high density of this same material mistakenly called "hard layers".

OBJECTIVE

In this study, a comparison is made between the interpreted soil parameters from CPTU tests and those obtained from laboratory tests on undisturbed samples, primarily focusing on the coefficient of horizontal and vertical consolidation (c_v and c_h) and the permeability (k_v and k_h). The above-mentioned effort was done taking advantage of the established works for a wide geotechnical investigation in the north area of former Chalco Lake, in the area denominated by Mooser (2002) known as "Narrow Tlapacoya" (Figure 1). Herein, the information from CPTU soundings is evaluated from three different sites where previous investigations were performed.

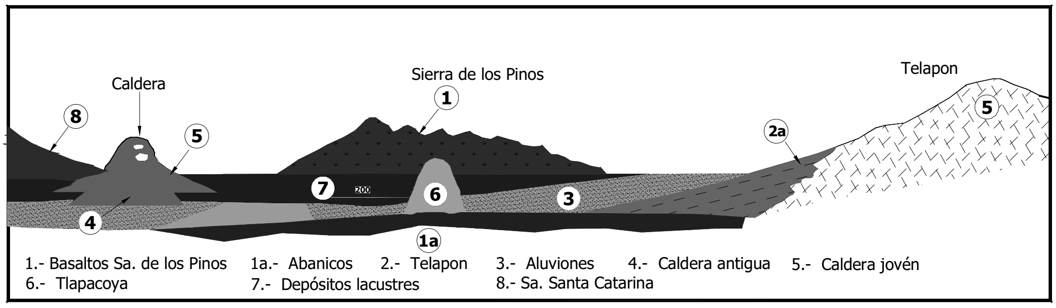


Figure 1. Geologic schematic section of former Chalco lake plain area (Mooser 2002)

PIEZOCONE TESTING

For the execution of these works, a type 2 (u_2) piezocone was used which is equipped with a porous element for porewater pressure measurement located immediately behind the tip. This cone is supplemented with a data acquisition system which records: the tip resistance (q_T), shaft resistance (f_s), pore pressure (u_2), penetration rate, and vertical inclination with depth. Due to the presence of superficial fill material at the three sites, shallow pre-drilling was carried out prior to cone penetration testing until the interface with the natural soils was detected. Starting from this point, the cone penetration advanced continuously until the projected depth was reached with a penetration rate of 10 mm/s ± 5mm, a value recommended by Santoyo et al. (1989) based on local experience obtained in the Mexico City lacustrine soils. Measured penetration test readings for the 3 sites are shown in Figure 2.

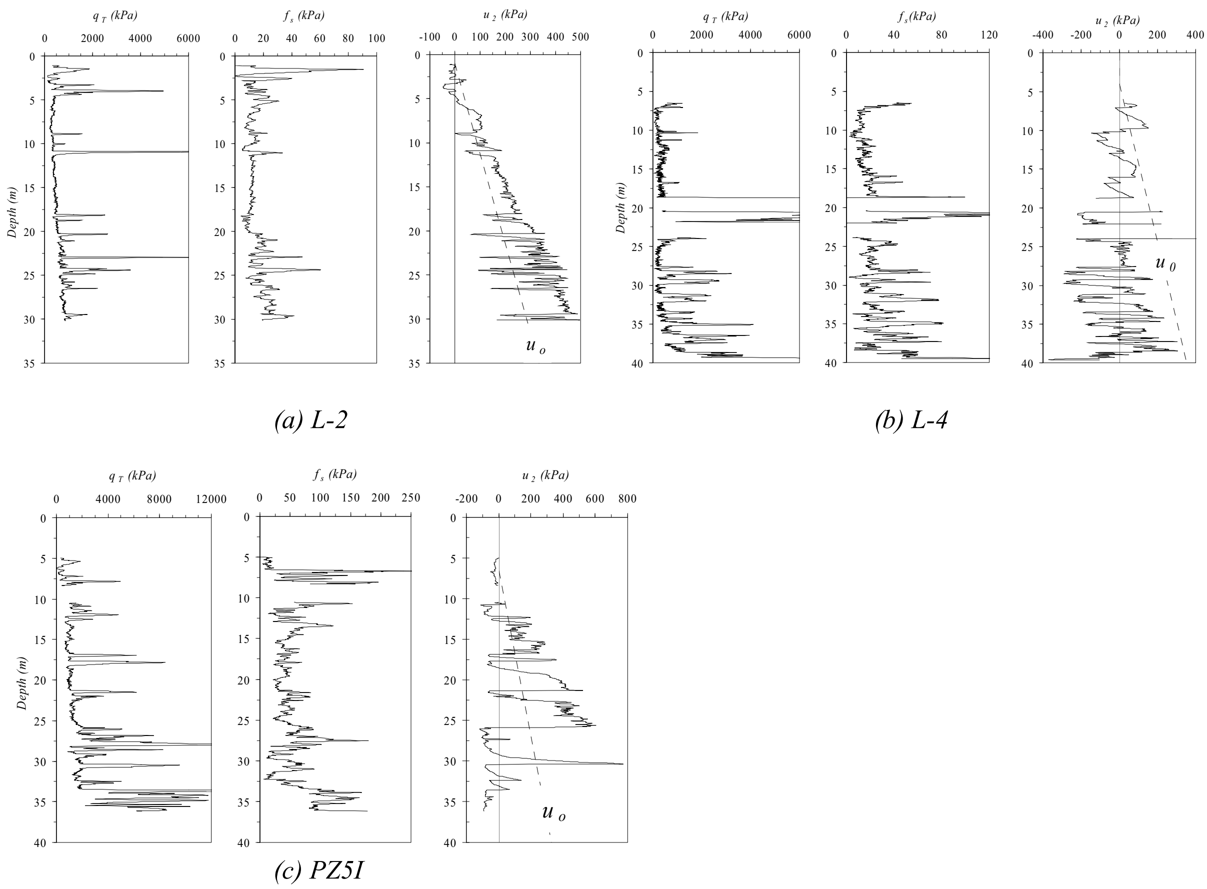


Figure 2. CPTU profiles at former Chalco Lake

COEFFICIENT OF PERMEABILITY AND COEFFICIENT OF CONSOLIDATION

The hydraulic conductivity, k_h, and the coefficient of consolidation, c_h, represents the fluid flow characteristics through the soil mass. The excess of pore water pressure generated during CPTU penetration can be recorded with regard to the time when carrying out stops during penetration (dissipation tests). Several methods for CPTU dissipation tests interpretation have been proposed (Teh & Houlsby, 1991), however the first approaches have only been developed for the monotonic pore water pressure response. With type 2 piezocones a dilatory response can be observed in preconsolidated and fissured materials where pore water pressure increases initially during the dissipation test until reaching a peak value diminishing with time until reaching an equilibrium pressure. This type of behavior has also been observed during pile driving in saturated fine soil.

In this article a mathematical solution based on the cavity expansion-critical state for the monotonic and dilatory response with regard to time (Burns & Mayne, 1998) was used. For practical use Mayne (2001) proposed a mathematical approach where instead of adjusting a single point of the field dissipation curve (t_{50}) the complete curve is adjusted to obtain the best global value of the coefficient of consolidation, c_h.

The excess pore water pressures, Δu_t, at any time can be compared with the initial values during penetration, $\Delta u_i = u_2 - u_0$ which c be represented by:

$$\Delta u_i = (\Delta u_{oct})_i + (\Delta u_\tau)_i \tag{1}$$

where: $(\Delta u_{oct})_i = (2/3)M\sigma_{vo}'(OCR/2)^{\Lambda} lnIr$, is the octahedral component during penetration and $(\Delta u_\tau)_i = \sigma_{vo}'[1-(OCR/2)^{\Lambda}]$ is the shear-induced component during penetration, ϕ' is the effective friction angle, $M = (6sin\phi')/(3-sin\phi')$, $a_k = (3-sin\phi')/(6-4sin\phi')$, $\Lambda = (1-\kappa/\lambda)$ and κ *y* λ = *compression and expansion index*. Substituting and reducing terms the pore pressure at any time, *t*, can be obtained in terms of the modified time factor T^* from:

$$\Delta u = \frac{(\Delta u_{oct})}{1+50T^*} + \frac{(\Delta u_\tau)}{1+5000T^*} \tag{2}$$

In this expression a modified time factor is used that is defined for:

$$T^* = \frac{c_h t}{a^2 (Ir)^{0.75}} \tag{3}$$

On a spreadsheet assumed logarithmic values of T^* are assigned to generate the corresponding time *t* for a given rigidity index, I_r, and probe radius, *a* (cone radius). Then, a trial & error procedure can be used to obtain the best fit c_h with which the theoretical curve fits best to the field curve (Mayne, 2002). In Figure 3 the field curves are compared with the calculated with Eqs. 2 and 3 using the following input parameters:

Table 1. Summary of geotechnical parameters used for Eqs. (2) and (3)

Site	Depth (m)	OCR	Ir	ϕ'	Λ	c_h (cm^2/s)
L-2	8,47	4,4	46	19	0,94	2,70 x 10^{-04}
L-2	11,10	8,0	40	17	0,94	2,90 x 10^{-03}
L-2	29,50	2,2	40	30	0,94	6,50 x 10^{-03}
PZ5I	16,27	2,30	40	23	0,94	9,50 x 10^{-04}

The coefficient of permeability in the horizontal or radial direction (k_h) can be obtained with field tests such as: the pumping tests, the Matsuo Akai permeability test, the Lefranc or USBR test among others. It is also possible to determine it in the vertical direction (k_v) with laboratory tests on undisturbed or reconstituted samples using constant or falling head permeameters or from the records from consolidation tests. If the coefficient of permeability in the horizontal direction can be estimated from a CPTU dissipation test by means of the correlation factors (k_h/k_v) proposed by Baligh and Levadoux (1980), then the permeability in the vertical direction can be calculated.

The method proposed by Parez & Fauriel (1988) Eq. 4 it is only applicable to a monotonic pore pressure response during in dissipation test where the t_{50} value can be defined with clarity.

$$k_h(cm/s) \approx \frac{1}{(251t_{50})^{1.25}} \tag{4}$$

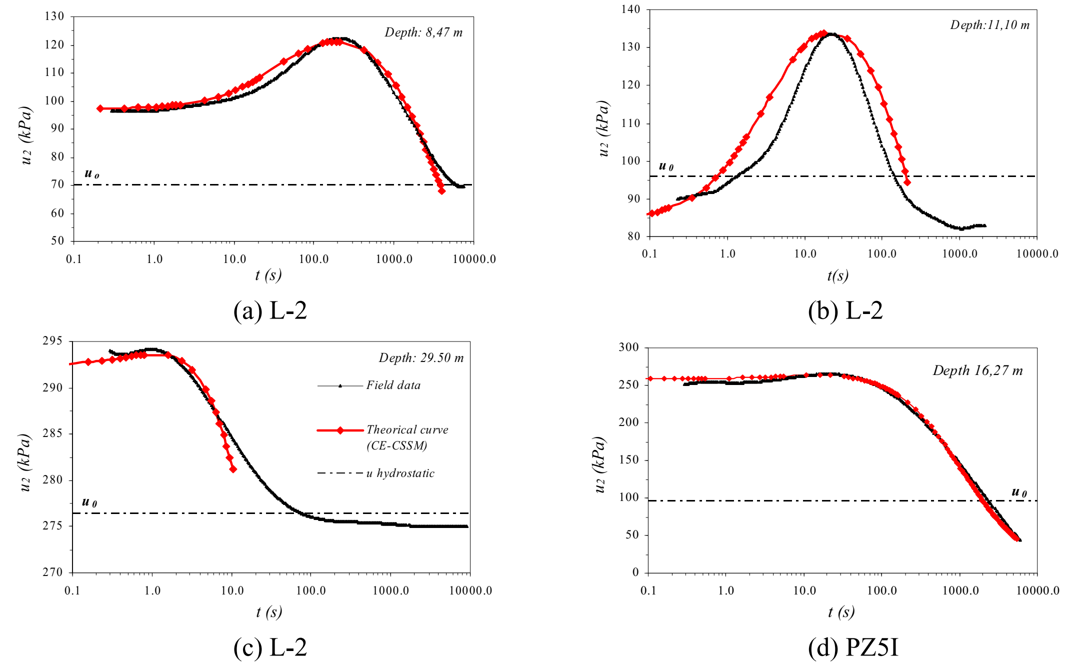


Figure 3. Field and theoretical dissipation test curves (L-2 and PZ5I sites)

Due to the dilatory pore pressure response in the dissipation tests carried out in the study area, Eq.5, proposed by Mayne (2001) was used herein.

$$k_h = \frac{c_h \gamma_w}{M} \tag{5}$$

In Eq. 5, *M* corresponds to the constrained modulus, which is the inverse of the volumetric compression modulus (m_v) calculated from consolidation test results; c_h is the horizontal coefficient of consolidation and γ_w the water unit weight. The values of *M* were obtained from the results of the correlation between CPTU and CPT records and laboratory tests results (Rivera, 2004).

It is important to note that the sample depth should be close to where the dissipation tests were carried out, however in Table 2 it is observed that the values obtained in laboratory and those estimated from CPTU dissipation tests are within the same range. An important aspect is the relationship that exists between the horizontal and vertical permeability at the L-2 site with a average of $k_h/k_v=0,66$.

Table 2. Summary of results from laboratory vs CPTU evaluations of coefficient of consolidation (c_{vh}) and permeability (k_{vh})

Laboratory		***CPTU tests***		***Ratio***	***Ratio***
c_v	k_v	c_h	k_h	c_h/c_v	k_h/k_v
(cm²/s)	**(cm/s)**	**(cm²/s)**	**(cm/s)**		
2,27 x 10^{-03}	6,18 x 10^{-07}	2,70 x 10^{-03}	3,31 x 10^{-07}	1,19	0,54
3,94 x 10^{-03}	6,54 x 10^{-07}	2,90 x 10^{-03}	4,38 x 10^{-07}	0,74	0,67
2,61 x 10^{-03}	7,45 x 10^{-07}	6,50 x 10^{-03}	5,79 x 10^{-07}	2,49	0,78
5,23 x 10^{-03}	3,03 x 10^{-07}	-----	-----	-----	-----
3,94 x 10^{-03}	4,91 x 10^{-07}	-----	-----	-----	-----

RIGIDITY INDEX

The prediction of the coefficient of consolidation, c_h, with the cavity expansion theory depends partly on using an appropriate value of the rigidity index, I_r. For clay and in general for fine grained soils the rigidity index, *Ir*, is the relationship between the shear modulus, *G*, and the undrained shear strength, S_u. For clayey soils the range for this parameter can be lower than 50 and larger than 600. Due to the wide range of values of the rigidity index value, the coefficient of consolidation estimated can change by a factor of 4. The value of I_r can be calculated by different means: triaxial tests with undisturbed samples, site tests such as pressuremeter and empirical correlations such as the ones proposed by: Keaveny & Mitchell (1986), Kulhway & Mayne (1990) and Mayne (2001). Based on the results of laboratory tests on undisturbed samples from the L-2 and L-4 sites, Rivera I. (2004, Professional Thesis) proposes an empirical correlation between the tip resistance (q_T) expressed in bars and the rigidity index with the following equation:

$$Ir = 15Ln(q_T) + 39 \qquad (6)$$

Figure 4 shows the *Ir* profiles estimated from Eq. 6 whose tendency agrees well with the laboratory profiles.

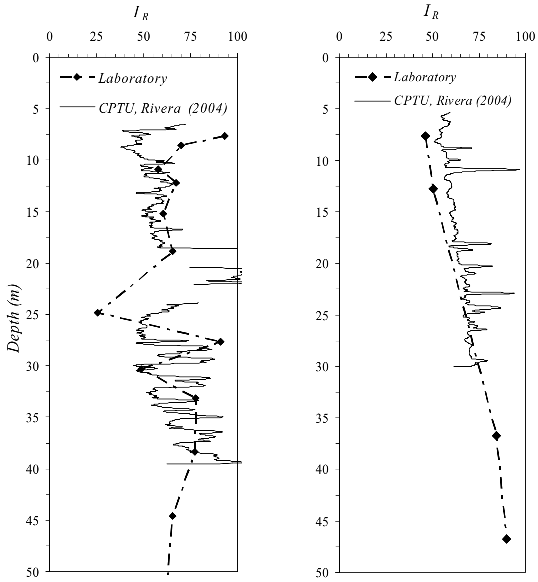
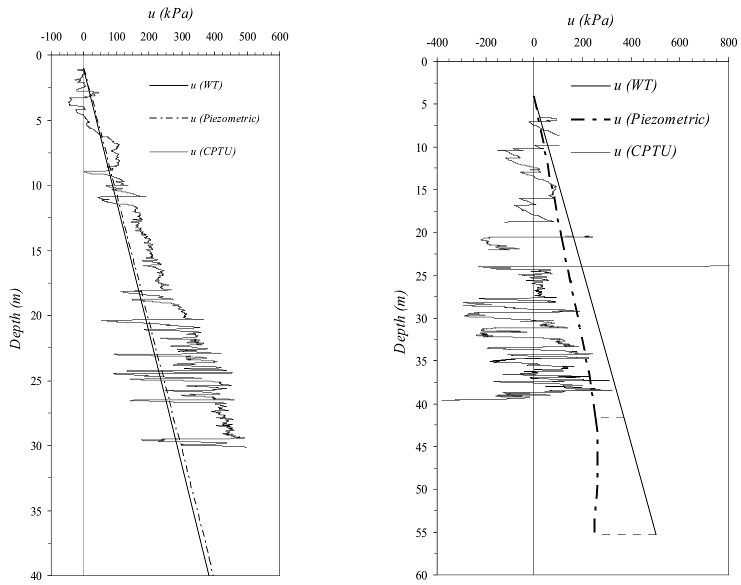


Figure 4. Estimated I_R profiles for: L-2 (a) and L-4 (b) sites

PORE PRESSURE DETERMINATION

The facility to record the pore pressure in a CPTU test provides a direct and fast way to obtain the hydraulic ground conditions. With the purpose of evaluating the equipment capacity as well as the efficiency of the obtained records, a comparison of the pore pressure profiles (u_2) and dissipation test curves was carried out with the records from piezometric stations installed in the same explored sites (L-2, L-4 and PZ-5I), all of them equipped with more than one open piezometer "Casagrande type" installed at different depths. The recorded CPTU pore pressure profiles, u_2, in the explored sites present interesting aspects such as negative pressures within superficial layers with a slight degree of preconsolidation Furthermore is it possible to identify the position of permeable layers where the pore pressure decreases rapidly and even some with values smaller than the hydrostatic or piezometric pore pressure.



L-2 L-4

Figure 5. Pore pressure profile for: L-2 (a) and L-4 (b) sites

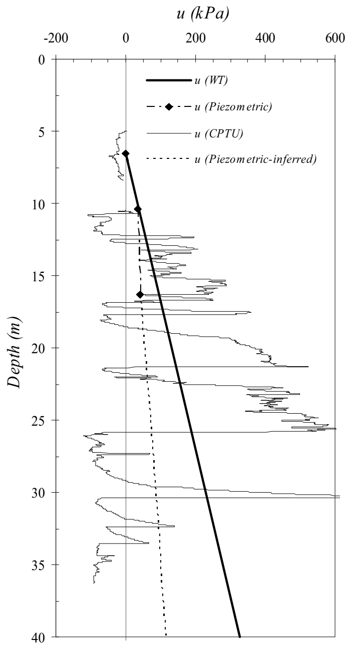


Figure 6. Pore pressure profile for PZ5I site

The equilibrium pore pressures reached with the dissipation tests on site L-2 site are similar to the hydrostatic and piezometric pressure with an error of ± 10% as shown in figure 5. With the reading of piezometric stations installed in L-4 and PZ-5I site a local pore pressure fall was detected (a common phenomenon in Mexico City Valley) that could be the possible reason of the negative CPTU pore pressures records as was observed in Figures 5 and 6. It is important to clarify that for the PZ5I site, the piezometric line starting from a depth of 16 m is inferred on the basis of information from nearby piezometric stations.

CONCLUSIONS

With the interpretation of CPTU dissipation tests using the method proposed by Mayne (2001), it is possible to estimate and compare the compressibility and the permeability in the horizontal direction with vertical values obtained by laboratory testing. Also, the CPTU-evaluated permeability is located within the ranges reported by the study carried out by Vargas and Ortega (2000) in this area.

The empiric equation proposed by Rivera, I. (2004) to estimate *Ir* (Eq. 6) it is only based on the results of this study. It would be beneficialif it could be verified that it could be applicable to other areas of the lacustrine Mexico City Valley as well as to different kind of soils elsewhere.

With the CPTU pore water pressures profiles (u_2) it is possible to locate permeable layers as well as low permeability soil layers that present a certain degree of preconsolidación. Likewise, it is possible to estimate the tendency of the pore pressures profile along the soil column. In comparison with the piezometers records the CPTU pore pressures recorded at L-2 and PZ-5I sites were lightly higher but one can say that they adjusted in a satisfactory way, while in L-4 site the values from CPTU records were lower than piezometers data, registering a great quantity of negative values possibly due to the piezometric site conditions.

The CPTU test is very useful to determine the hydraulic properties of soils in a relatively short time, either by means of the execution of dissipation tests or by means of the analysis of the pore water pressure profile u_2, however, in those places where a lot of uncertainty exists in this respect, it is advisable to install instruments with the purpose of corroborating the information.

Due to the wide geotechnical knowledge and acquired decades of experience in the soft lacustrine Mexico City Valley soils, it is possible to calibrate the CPTU test and make use of the vast information available, thus securing this technology as a common exploration technique for future geotechnical investigations in this area.

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