Finite Element Soil-Pile-Interaction Analysis of Floodwall in Soft Clay

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ABSTRACT

A 2D plane strain finite element model was used for soil-pile interaction analyses to investigate the basic performance of the Floodwall under hurricane loadings. A lateral pile load test was used to develop soil resistance characteristics of the soft clay at the construction site for the large-diameter pile. The 3D soil resistance response in front of the laterally loaded pile was taken into consideration in the 2D model by using appropriate modified soil parameters. A soil wedge was also introduced into the finite element model to take into account the group effect of closely spaced piles of the Floodwall. The finite element model of the Floodwall was verified with a discrete p-y curve based substructure model and limit equilibrium state analyses. The good agreement between numerical results indicates rigorousness of finite element modeling for the soil-pile interaction of the Floodwall.

INTRODUCTION

The Inner Harbor Navigation Canal Lake Borgne Barrier Floodwall is an important component of the Hurricane and Storm Damage Risk Reduction System in New Orleans, LA. The Floodwall is comprised of large diameter cylindrical pre-stressed concrete piles driven closely together and braced by steel-pipe batter piles. The precast post-tensioned roller spun concrete piles of the Floodwall are 1.7 m in diameter with a 15.2 cm wall thickness and are about 44.2 m in length. They were driven into the ground to a depth of 35.1 m from ground surface at EL-4.6 m with a center-to-center spacing of 1.8 m. The batter steel pipe piles of the Floodwall are 0.91 m in diameter with a wall thickness of 1.9 cm above EL-8.2m and 1.3 cm below, and they were driven to EL-57.9m with a batter angle of 34 deg and center-to-center spacing of 3.7 m. The general soil profile at the construction site consists of Holocene age Marsh and soft clay overlying Pleistocene deposits. The soft clay foundation conditions and large storm surge loading combine to create challenging design conditions. A safe and economical design of the Floodwall "floating" in soft-medium-stiff clays required a thorough understanding of the soil-pile-interaction to satisfy design requirements for structural strength and serviceability. For this purpose, soil finite element models were developed using the PLAXIS geotechnical computational package (Brinkgreve, 2002) to investigate the basic performance of the Floodwall under hurricane loadings.

To better model the soil-pile-interaction behavior the lateral resistance of the soft clay to the large-diameter pile loading was evaluated based on a lateral pile load test. The corresponding in-situ stiffness's of soft clay under the single pile deformation were derived from the field-measured soil resistances and were used in a 2D finite element model to reflect the 3D pile-soil-pile-interaction of the concrete test piles. The good agreement of numerical predictions with field measurements supports the reconciliation of soil stiffness's with the *p-y* interpretation from the lateral pile load test and the rigorousness of the finite element modelling for the soil-pile interaction. Using the soil wedge concept the group effect of closely spaced vertical cylinder piles of the Floodwall was taken into consideration in the soil finite element model. The storm surge induced net pressures on the vertical pile wall below the mudline were derived from the finite element soil-pile-interaction analysis and were applied in a p-y curve-based GROUP verification model of the Floodwall. A very good agreement of the design bending force of the vertical pile was found between the finite element analysis and GROUP model.

FINITE ELEMENT MODELING

In the 2D finite element model of the Floodwall, the plate (or beam) element was used for both vertical and batter piles. The properties of structural elements (e.g. axial stiffness and flexural rigidity) were determined by dividing pile properties by the corresponding pile center-to-center spacing. The same approach was also applied to define unit weights of beam elements. The connection of the vertical pile to the cap beam is fixed, but a pinned connection was used for the batter pile to cap beam connection. Foundation materials were modeled using high order triangular elements with a finer mesh in the soil wedges adjacent to vertical piles. Interface elements were created between the soil and structure elements and a strength reduction factor was applied for soil-pile interface. The standard fixity boundary conditions were used in the finite element model, i.e. fixed in horizontal direction on the vertical boundaries and fixed in both *x* and *y* directions on the bottom of the model. A close boundary condition was also set on the bottom of the model during the groundwater seepage calculations. Figure 1 shows the finite element model configuration at the local area near the Floodwall. The calculation phases in the finite element modeling include major construction sequences, such as (i) construction of the dredged channel from the original mudline to EL-4.6 m for (ii) the construction of the Floodwall and (iii) placement of scour stone layer on the protected side of the Floodwall afterward. After these construction phases, additional calculation phases were created for the variety of design load cases. Although the Mohr-Coulomb (MC) soil model was used in finite element analyses of the Floodwall to describe the soil reaction behavior to pile deformation under the hurricane conditions, the advanced Hardening Soil (HS) model (Brinkgreve, 2002; Duncan and Chang, 1970) was also considered during the model verification with the lateral pile load test as described in the ensuing section. All these models require the good estimates of soil lateral resistance characteristics to the deformation of the large-diameter pile in soft clay at the site.

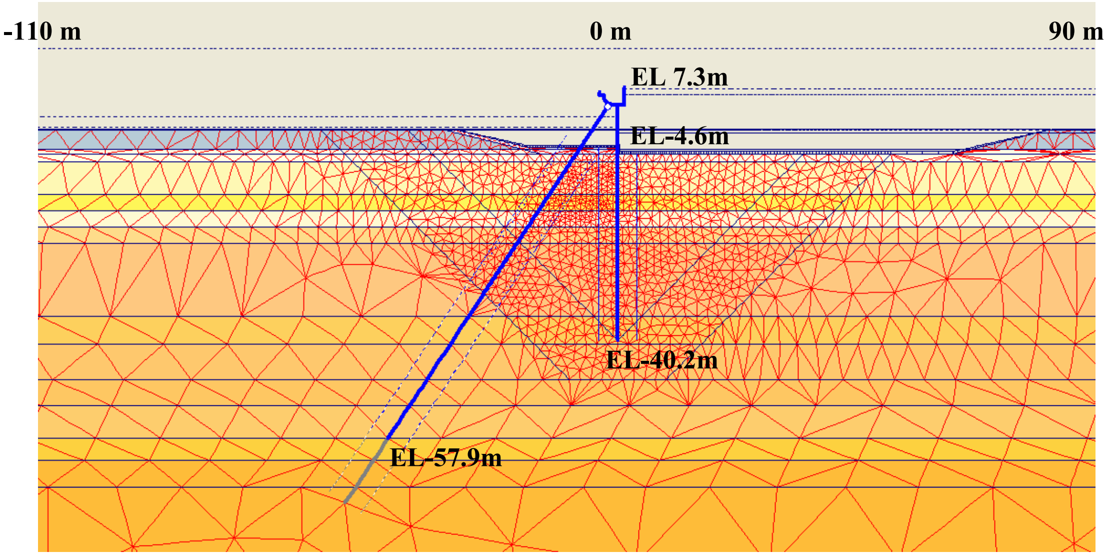

Figure 1. Finite element model configuration near the Floodwall.

DESIGN SOIL PARAMETERS

General soil profile

General geological profiles at the construction site include a very soft organic surficial clay (or Marsh) underlain by the Interdistributary and Prodelta soft clay deposits, which mantle the Pleistocene medium and stiff clay. In some areas, a thin intrusion layer of nearshore gulf (interdelta) sand overlays the Pleistocene clay. Both borings and CPTs (Cone Penetrometer Test) were made at several locations to determine the soil profile and shear strengths along the structure alignment. Laboratory testing results on borings and field investigation from CPTs were used to develop the correlation of soil shear strengths S_u with initial vertical effective stresses σ'_{v0} (assuming normal consolidation) at the project site. The soil profile and design soil shear strengths for a typical Floodwall design reach that is under the consideration in this paper are shown in Table 1.

Table 1. General design soil profile and key parameters for the considered design reach of the Floodwall

Elevation (m)	Profile	γ_{sat} (kN/m^3)	S_u (kN/m^2)	ν_u
0 to -3.7	Peat	10.8	4.8	0.4
-3.7 to -6.1	Marsh	16.5	5.0	0.4
-6.1 to -15.2	Interdistributary	15.7	$0.25\sigma'_{v0}$	0.4
-15.2 to -18.3	Prodelta	17.3	28.7	0.4
-18.3 to -21.3	Prodelta	19.7	30.2	0.4
-21.3 to -35.1	Pleistocene	18.1	$0.25\sigma'_{v0}$	0.42
Below -35.1	Pleistocene	17.4	$0.22\sigma'_{v0}$	0.45

Soil stiffness modulus

The undrained Young's modulus E_u of cohesive soil can be determined from the stress-strain curve from laboratory testing (e.g. unconfined compression test or triaxial test) or from direct field testing, such as with a Pressuremeter. Soil stiffness can also be derived from correlations with undrained shear strength S_u, tip resistance q_c of CPT or SPT (Standard Penetration Test) N values (Kulhawy and Mayne, 1990). The Young's modulus of soil determined from laboratory tests or from correlations as mentioned above is related to soil "ideal" three-dimensional stiffness behavior. Ideal soil properties are typically used in soil modeling and the project geometry and boundary constraints then govern the system response. When calibrating a 2D model to the results of a 3D single pile load test, and then using those results to model the near plane strain condition of the Floodwall, greater attention needs to be paid to the soil stiffness modulus. In the lateral load test the soil arching effect around a single pile results in a lateral resistance that is much stronger than what is represented in a continuous plane strain model. Based on results from a lateral pile load test conducted by Reese and Associates (2009), the soil stiffness modulus was modified to take into consideration the soil lateral resistance characteristics of soft clays to the to large-diameter piles of the Floodwall in the 2D plane strain model.

Lateral pile load test

A lateral pile load test was performed on a prototype cylindrical precast post-tensioned concrete pile of the Floodwall. The soil condition at test location is similar to the one as described in Table 1, except that two thin sand intrusion layers were found from EL-10.1m to EL-12.8m and from EL-20.1m to EL-21.3m. Inclinometers were installed inside the test pile on diametrically opposite locations along the loading direction to measure lateral response of the test pile under the various loads. Strain gauges were also installed at the different depths with approximate 3-meter spacing inside the test pile on diametrically opposite locations on the loading direction to measure the level of strain suffered in the test pile during each loading step. Strain measurements were used to derive the corresponding forces generated during loading on the test pile. Together with measurements of pile deflections and forces in the pile during each loading step, *p-y* curves were then derived at the particular locations of instruments, which represent lateral load-transfer characteristics of piles to surrounding soil at different discrete layers.

Modified Matlock approach

Site specific *p-y* curves were used to back calculate the design parameters using a substructure model based on the Matlock procedure (1970). Based on the parametric study of several lateral pile load tests in South Louisianan, Lee and Gilbert (1979) revised the Matlock *p-y* curve procedure for soil lateral resistance of soft clays to large diameter piles. They suggested that in order for the Matlock procedure to generate measured load transfer characteristic for the large diameter piles in very soft clay in South Louisiana, the cohesion c_u in Matlock procedure used for determining the ultimate soil resistance p_u should be increased to 2.6 times of the soil shear strength; and the deformation at one-half the ultimate soil resistance, y_{50}, should be reduced 25 times from Matlock's recommendation. The difference between the Matlock approach and the revision by Lee and Gilbert is shown below

$$c_u^{'} = 2.6\,S_u = 2.6\,c_u \tag{1}$$

$$y_{50}^{'} = (2.5/25) \times \varepsilon_{50} \times B = y_{50}/25 \tag{2}$$

where B is pile diameter, ε_{50} is the Matlock recommended axial strain for 50% of soil strength for different types of clay, c_u and y_{50} are cohesion and deflection at one-half soil resistance recommended by Matlock, c'_u and y'_{50} are the revised cohesion and y_{50} suggested by Lee and Gilbert.

A LPILE model (Reese et al, 2004), developed by Ensoft based on the Matlock procedure, was used for the investigation of the lateral pile load test. The ε_{50} and the soil cohesions were modified as discussed above to compensate for the discrepancy between LPILE and the modified procedure suggested by Lee and Gilbert. The incrementing load is applied at the pile top where a free head condition matches the load test. Figure 2 shows measurements of load-deflection behavior at pile top and corresponding numerical results obtained from the LPILE model with modified soil parameters, i.e. c'_u and ε'_{50}. The horizontal sections within the measurement plot represent creep of the pile after each load increment. For comparison, the numerical results obtained from LPILE using the original Matlock recommendations on cohesion and ε_{50} is also shown in Figure 2.

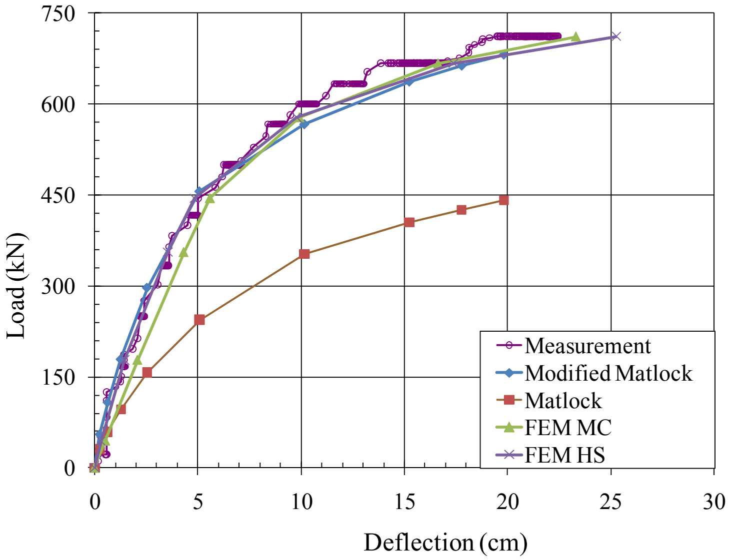

Figure 2. Test measurements and numerical predictions of load-deflection behavior at the top of the test pile in the lateral pile load test.

As can be seen from Figure 2, numerical predictions of load-deflection behavior at the top of the test pile, obtained from LPILE with the original Matlock procedure does not correlate well with the field testing measurements. However, the modified Matlock procedure, as indicated previously, does provide close results to the testing measurements. In addition to LPILE results, Figure 2 also includes computational results from two plane strain finite element models using MC and HS constitutive laws. Good agreement of finite element modeling results with test measurements supports the selected effective stiffness modulus in the 2D model when considering the soil-pile interaction effect in front of the pile.

Effective stiffness modulus

The modified c'_u and ε'_{50} as discussed in the last section are no longer corresponding to pure soil properties; but they reflect soil *p-y* curves of soft clays relative to the large diameter pile. Using these revised parameters, the effective soil stiffness modulus E'_s is defined in terms of the following relationship (Skempton, 1951),

$$E_s^{'} = c_u^{'} / \varepsilon_{50}^{'} \tag{3}$$

The introduction of the modified stiffness modulus E'_s represents appropriate soil resistance behavior in the finite element modeling to the large diameter pile in soft clay in South Louisiana. For this purpose, finite element models were created to simulate load-deflection behavior of the test pile in the lateral pile load test.

The PLAXIS geotechnical finite element code was used for this numerical study and both MC and HS models were considered for simulating the soil reaction behavior. In MC model, an elastic and perfectly-plastic constitutive law is assumed for the soil, and the yield surface is fully defined by model parameters and not affected by plastic straining. In the HS model, a hyperbolic model is used to represent the relationship between the vertical strain and deviatoric stress of the soil under the primary triaxial loading (Duncan and Chang, 1970). The plate element was used for the test pile,

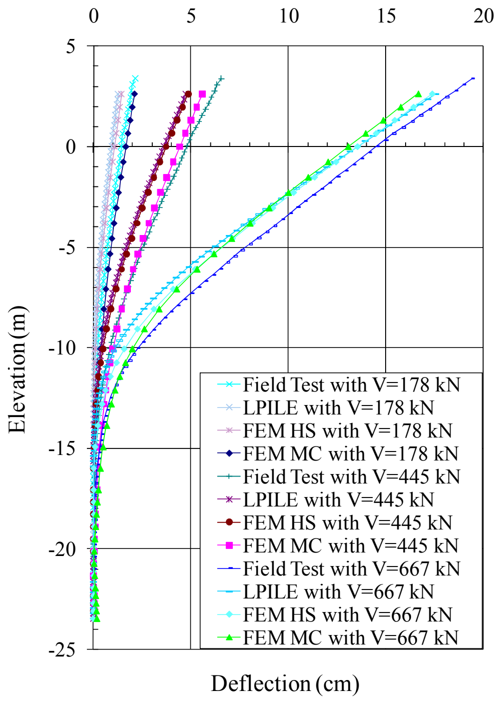

Figure 3. Comparison of measured deflections of test pile with numerical results from finite element and LPILE predictions.

and structural properties of the plate element, such as axial stiffness and flexural rigidity, were determined by dividing pile properties by the pile diameter. As in the LPILE model, the soil profile used in finite element modeling was defined by the borings and CPTs near the test location. The modified c'_u and E'_s were used in both finite element models as soil parameter inputs. The incremental loads were applied at the pile top, and nonlinear structural effects of the test pile with increased load was also considered in the finite element modeling to account for micro-cracking of the concrete pile. Figure 3 shows test measurements (from inclinometers) and finite element modeling results of pile deflections under different lateral loadings at the pile top during the lateral pile load test. As a comparison, LPILE model results are also shown in Figure 3. The good agreement of numerical predictions with measurements indicates the reconciliation of soil stiffness's with the *p-y* interpretation of soil lateral resistance from the lateral pile load test and rigorousness of the finite element modeling for the soil-pile interaction as long as the soil parameters are appropriately chosen.

GROUP EFFECT IN FEM MODEL

Soil wedges for group effect

The discussions presented in previous sections were based on a single pile or isolated pile far from other piles. When piles are close to each other, like the vertical piles of the Floodwall, the activated passive soil wedges in front of each laterally loaded pile will interface with each other, inducing the overlap zone between soil wedges of adjacent piles (Ashour, 2004). Such overlapping will result in an increase in the soil stress level within the interfered passive wedge of the pile, and consequently leading to an increase in strain based on the stress-strain relationship of the soil. Such softening response of the soil due to the soil wedge interaction within the pile group is commonly taken into account using group interaction factors, such as either p- or y- multiplier, which serve two purposes: softening the response at all values of deflection, and reducing the ultimate passive capacity of the supporting soil. Usage of such p- or y- multiplier is equivalent to reducing modulus of subgrade reaction, accounting for reduced resistance due to soil wedge interaction.

The group effect can be implemented in a 2D continuous soil finite element model using a soil wedge approach. The depth of the passive soil wedge is dependent on the pile deflection (Ashour, 1998), but it is usually assumed that such passive soil wedge has a triangular shape and forms from the pile tip to ground surface with an angle β to the vertical pile, as defined in below

$$\beta = 45^\circ + \phi / 2 \tag{4}$$

where ϕ is the internal friction angle of the soil. A p-multiplier p_M was directly applied to soil cohesion parameter c_u to reduce the soil ultimate resistance in the soil wedge for the group effect, i.e.

$$(c_u)_{wedge} = c_u \cdot p_M \tag{5}$$

Consequently, the soil stiffness modulus was also reduced by the p-multiplier based on the correlation as shown in (3).

SOIL-PILE INTERACTION OF FLOODWALL

Modeling considerations

Based on the calibration with the lateral pile load test and LPILE modeling, the finite element MC model was developed to investigate soil-pile interaction of the Floodwall with the soft soil foundation. The general description and finite element model configuration were given at the beginning of this paper. As can be seen in Figure 1, soil wedges were defined in the vicinity of the vertical pile of the Floodwall for consideration of the group effect. An appropriate group effect factor (p-multiplier) was selected by existing recommendations (Wang, 1986) based on vertical pile spacing. The p-multiplier was then applied to the soil stiffness modulus in the soil wedge zone in front of the vertical piles based on the loading direction, to model the appropriate soil lateral resistance in plane strain. However, the original soil shear strength was used for cohesion parameters in the finite element model due to several considerations. First, the bracing support from the batter pile to vertical pile wall is mainly due to the axial skin friction of the batter pile, which is directly related to the soil cohesion of the clay. Secondly, an increase of soil cohesion could result in an unrealistic lower active earth pressure on the pile wall under the plane strain water surcharge during hurricane loading in the 2D model. The finite element soil-pile interaction analyses were used to determine design bending forces on the vertical pile of the Floodwall. Figure 4 shows the computational results of the unfactored bending moment distribution along the vertical pile corresponding to critical design load case including a high storm surge water pressure on the flooded side.

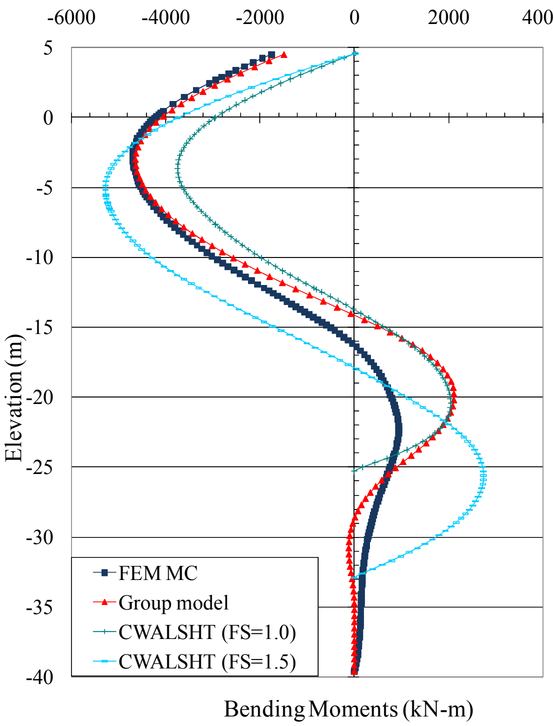

Figure 4. Comparison of bending moment distributions along the vertical pile obtained from PLAXIS, GROUP and CWALSHT models.

Model results and comparisons

Figure 4 also includes numerical results for a *p-y* curve based GROUP model. In this GROUP Model, a 11-meter section with seven vertical piles and three batter piles were included. The diameter as well as related axial and bending stiffnesses of the first and 7th cylinder piles have been reduced in order to achieve ratio of 2 vertical piles to 1 batter pile of the typical flood wall section. As in the finite element model, pile connections were modeled as fixed for vertical piles and pinned for batter piles. Due to the same consideration as mentioned in the last section, the modified ε'_{50} and soil shear strength were used in GROUP model to derive the *p-y* curves. To have correct results, an appropriate external pressure was applied on the pile wall in GROUP model. This external pressure includes a hydraulic pressure above the mudline and a hydraulic-induced net pressure below the mudline on the wall. This net pressure reflects the global soil mass pressure and pore water pressure on the pile wall due to the water differential head on the either side of the flood barrier system. Conventional steady-state analysis is not applicable in this scenario since pore flow will not reach the steady state in clays with low permeabilities during the relative short storm period. On the other hand, pure transient seepage analyses can not include the effect of excess pore pressure under the water surcharge. The active net pressure on the pile wall is the result of soil-structure interaction for the Floodwall with clays under the storm surge surcharge. Therefore, an external net pressure derived from finite element modeling was used in the GROUP model.

As a design check, a limit equilibrium procedure was also performed for the typical cross section of the Floodwall using the USACE CWALSHT computer program with the design load case mentioned above. The braced pile wall was modeled as an anchored retaining wall with an anchor force applied at location of the batter pile top. The effect of high surge level on the flooded side of the wall, i.e. lateral water pressure on the wall and water surcharge on the ground surface, were considered in the CWALSHT model. Two factors of safety, FS=1.0 and FS=1.5, at level 1 (on both active and passive sides) were used in the CWALSHT analyses and they were held constant for all the analyses performed. The corresponding bending moment of the vertical pile of the Floodwall obtained from the CWALSHT method with the first level FS=1.0 and 1.5 are also shown in Figure 4. As can be seen in Figure 4, the computational results of bending moment obtained from continuous FEM and substructure discrete GROUP match very well and they fall between the two limit equilibrium CWALSHT results. The discrepancy in the numerical results below EL-50ft likely result from the interpretation of the external net pressures on the structure.

CONCLUSIONS

Soil parameters are very important in finite element modeling of soil-structure/pile interactions. By using appropriate soil parameters, three-dimensional pile-soil-pile interaction due to soil arching and group interaction effects can be modeled in the plane strain finite element model. Soil-pile interaction was evaluated using a set of *p-y* curves in the discrete model based on the conventional approach of a 1D beam on an elastic foundation. For finite element modeling of the Floodwall, attention needs to be paid on selecting soil parameters such that appropriate soil reactions to both lateral pile deflection and vertical plane-strain water surcharge can be captured in the same model. The proposed procedure for soil-pile interaction in a plane strain model was mainly based on the calibration with a lateral pile load test and parametric study using the Matlock *p-y* curve based procedure. More efforts will be needed for the investigation of the theoretical mechanism behind these numerical observations, possibly using the recently developed soil strain wedge concept.

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