STRUCTURAL RESPONSE UNDER TSUNAMI-INDUCED VERTICAL LOADS

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Abstract

To design or assess the capacity of buildings to be used as tsunami vertical shelters, a proper consideration of the effect of tsunami-induced loads on the structural capacity is essential. The field of tsunami engineering is relatively new and great efforts have been made so far for the definition of performance-based methodologies able to predict the behaviour of buildings inundated by onshore tsunami flows. Despite these efforts, current international guidelines for the tsunami design of buildings do not explicitly state how to apply tsunami loads on buildings in a non-linear structural analysis approach. Recent studies have proposed a non-linear static analysis method, called the Variable Depth Pushover (VDPO2), for assessing the performance of buildings under the horizontal hydrostatic pressures induced by a tsunami flow. This methodology was developed under the assumption that buildings are watertight which is representative of new-designed buildings with tsunami-resistant external cladding. The effect of tsunami-induced vertical loads on structural members has not been addressed in this context. In the case of buildings with breakaway claddings (e.g., masonry infills), the water flow passing through the building induces vertical load components on the structural members, due to uplift and buoyancy pressures, that might affect the overall structural capacity. This paper presents a preliminary study to understand whether the consideration of tsunami-induced vertical loads in structural analysis, and their integration into an ASCE methodology for structural analysis, is necessary or not for a proper design/assessment of tsunami shelters. The effects of vertical loads induced by onshore tsunami flows are herein considered for reinforced concrete (RC) frame structures with breakaway infills. The vertical loads are defined in accordance with the ASCE 7-16 Standard load definition and are applied to the structure incrementally in accordance with the VDPO2 approach. The analysis is conducted for vertical loads only, in order to point out their effects on the structural capacity independently from the horizontal demand. Three case-study RC frames representative of low, mid and high-rise existing buildings in the Mediterranean area are used in this investigation. The analysis results demonstrate that the effect of tsunami-induced vertical loads are significant on the overall structural capacity, as they decrease the compressive axial load in columns resulting in a consequent reduction in both flexural and shear capacity. It is therefore recommended that vertical tsunami loading be explicitly considered in the evaluation of the tsunami performance of structures, (in particular for RC buildings), where floors above ground level are expected to be submerged by tsunami inundation.

Keywords: tsunami assessment, tsunami design, uplift, buoyancy, variable depth push over, VDPO2

1. Introduction

The risk of natural disasters affecting coastal communities worldwide is rapidly increasing, pushing researchers to develop reliable methodologies for predicting the losses related to such hazards. Tsunami events have a low frequency but can induce high human and economic losses on coastal communities. Hence, the design and assessment of structures against tsunami-induced loads is fundamental for estimating the resilience of the built environment to such hazard and to informed evacuation practice.

Only few studies have defined methodologies for assessing the capacity of structures impacted by tsunami onshore flows [1-3]. Among these, a nonlinear static procedure, called Variable Depth Pushover, VDPO2, for assessing the performance of structures subjected to tsunami horizontal loads has been developed by Petrone et al. [4] and improved by Baiguera et al. [5,6] to be used with the provisions of the recent ASCE 7-16 Standard [7]. However, current structural analysis methods (including VDPO2) consider only tsunami-induced horizontal loads, distributed along the seaward columns, and neglect the vertical pressures induced by a tsunami flow on structural members when the external cladding breaks away.

This paper presents a preliminary study to understand the importance of including the tsunami-induced vertical loads into an ASCE methodology for structural analysis. The vertical pressures induced by a tsunami onshore flow as defined by the ASCE 7-16 Standard provisions for structures with breakaway infills or openings are first presented. Then, these vertical loads are applied to three case study reinforced concrete (RC) frames with breakaway infills, representative of low, mid and high-rise existing buildings of the Mediterranean area. For this analysis, the vertical loads are applied incrementally, simulating the stages of tsunami inundation of the frames and sequential submergence of upper stories as the inundation depth increases, in accordance with the VDPO2 approach. Only the vertical loads are applied, in order to assess and quantify their effects on the structural capacity of members in terms of axial load variation, shear and flexural capacity of columns.

2. Vertical loads according to ASCE 7-16

According to ASCE 7-16 Standard [7], a tsunami flow induces vertical pressures on the horizontal members of a building with openings (when the opening ratio > 25%) or with breakaway infills. These vertical pressures comprise hydrostatic and hydrodynamic components. It should be noted that these load components do not apply to the case of watertight buildings, where the vertical loads due to buoyancy act only at the foundation level according to ASCE 7-16.

Hydrostatic vertical loads include:

- **Buoyancy due to air pocketing.** Buoyancy includes the effect of air pockets trapped below floors, for instance in the case of frames between consecutive beams and the lower edge of the slab (see Fig.1b). The uplift pressure p computed as in Eq.(1):

$$p = \gamma_s h^* \quad (1)$$

where $h^*=h_{beam}$ is the net height of the beams with respect to the slab.

- **Buoyancy due to enclosed space.** The uplift pressure caused by buoyancy on upper slabs is induced by enclosed spaces in partially submerged buildings before the external infills (or windows) break away. All windows, except those designed for large missile wind-borne debris impact or blast loading, can be considered broken away when the inundation depth reaches the top of the windows or the expected out-of-plane capacity of the windows. The uplift pressure on slabs due to hydrostatic buoyancy can be still computed as in Eq.(1). However, in this case h^* should also include the height of displaced volume of water, as depicted in Fig.1c.

- **Buoyancy due to submerged members.** When RC members and slabs are fully submerged, they are subjected to a reduction of their self-weight caused by the volume of water displaced, see Fig.1d. In this case, given the assumption of the element's full submergence, according to Archimedes' principle, no surcharge given by the water above the submerged slab should be considered.

Conversely, hydrodynamic tsunami-induced vertical loads consist of impulsive pressures caused by the **surge uplift**. According to ASCE 7-16 provisions, a minimum average hydrodynamic uplift pressure of 20 psf (0.958 kN/m^2) applied to the soffit of the slab should be considered due to the surge uplift.

It should be noted that, according to the ASCE 7-16 definition, the tsunami-induced vertical loads are only a function of the inundation depth and, differently from horizontal loads, they do not depend on other tsunami parameters (e.g., velocity or Froude number). The standard defines two load combinations that should be considered for tsunami design or assessment, where D=dead loads, L=live loads, T_{su}=tsunami loads:

$$\begin{gathered} \textit{COMBO 1)}\ 0.9D + Tsu \\ \textit{COMBO 2)}\ 1.2D + 0.5L + Tsu \end{gathered} \tag{2}$$

Both load combinations have been considered herein for assessing the effects of tsunami-induced vertical loads on structural members, with T_{SU} in this case comprising only the vertical tsunami loads. Considering the failure of external claddings or the presence of openings, the tsunami-induced vertical loads acting on structural members are applied incrementally, simulating the stages of tsunami inundation of the frames and sequential submergence of upper stories as the inundation depth increases, in accordance with the VDPO2 approach. The main critical steps of this incremental procedure are depicted in Fig.1, for a frame subjected to an increasing tsunami inundation depth of H_W, where the frame has a constant inter-storey height h, beams with depth h_{beam}, and infills that undergo out-of-plane failure at a water depth H_{OOP}. The procedure consists of 4 main phases and is described for the case of breakaway infills, but can be easily adapted to the case of windows that break away. For each phase, the value of h^* to be used in Eq.(1) is also reported.

In Phase 1, the inundation depth is less than H_{OOP}, hence, the water is retained outside the building and no vertical loads are acting on the upper-structure, see Fig.1a. In Phase 2, the ground-storey infills break away and the water passes through the building but no uplift pressures are induced on the first storey slab until the water depth H_w achieves the lower edge of the beams, creating air pockets between the beams and the slab that induce uplift pressures on the soffit of the slab, see Fig.1b. During the analysis, it is assumed that the slabs are able to carry on the uplift pressures induced by the tsunami and to transfer them to the beams without any failure. When the water depth first exceeds h (Phase 3), the first storey infills will not immediately break away, and additional uplift pressures will act on the slab from buoyancy due to enclosed spaces at the first-storey of the building, as shown in Fig.1c. These uplift pressures increase with the inundation depth until the collapse of the first-storey breakaway infills (Phase 4), see Fig.1d. In this phase, the first storey slab is completely submerged and only uplift pressures due to air pockets and buoyancy due to the submerged members are acting on the slab. The same load progression applies to upper stories for higher inundation depths. In the case of flat slab structures, air pockets are unlikely to form and their uplift effect should not be considered during the incremental analysis.

Due to their highly transient nature, hydrodynamic surge uplift and bore-front loading have not been included in the pushover procedure, assuming a tsunami steady state flow.

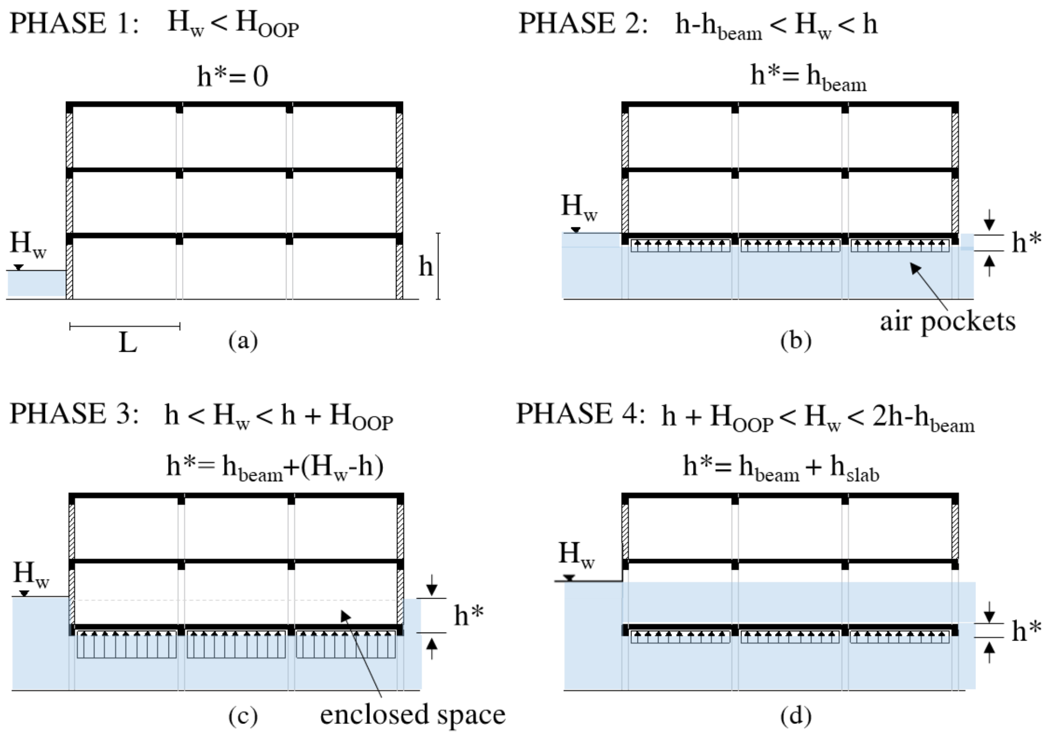


Fig. 1 – Tsunami-induced vertical loads on slabs for increasing inundation depth H_w.

3. Application to case study RC frames

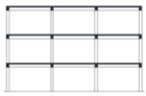
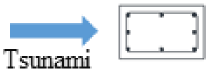
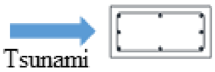
To investigate the effects of tsunami-induced vertical loads on buildings, a set of case study reinforced concrete (RC) frames has been defined and the axial load variation in first storey columns caused by uplift and buoyancy pressures has been assessed.

3.1 Definition of case study frames

Three buildings have been designed for gravity loads only according to the allowable stress method, in order to be representative of low, mid and high-rise buildings built before the 1980s in the Mediterranean area. One interior frame of each building has been selected as case study, as shown in Table 1, and the tsunami inundation flow is assumed to be parallel to the selected frames. The interstorey height, *h*, is assumed to be 3m and the bay span, *L*, is 5m. Dead loads are equal to 4.0 kN/m^2, live loads are considered equal to 3.0 kN/m^2. A concrete compressive strength of 20 MPa and a steel with 380 MPa yield strength are selected. The details of the ground-storey column cross-section are also shown in Table 1. For simplicity, it is assumed that all columns of the frame have the same cross-section details both in plan and elevation.

Exterior columns are usually encased in the external claddings and they have maximum inertia (if the cross-section is not symmetric) in the orthogonal direction to the tsunami flow. Conversely, the orientation of interior columns in buildings designed for gravity loads can be very variable, being based on architectural needs more than on structural considerations. For these case study frames, interior columns are oriented with their longer dimension in the tsunami flow direction.

Table 1 – Case study building frame details

	Low-rise	3 storey	Mid-rise	6 storey	High-rise	9 storey
Case study RC frames						
Ground storey interior columns	COLUMN 300x300mm A_s=6 ϕ14 ϕ 6/300mm 		COLUMN 300x550mm A_s=8 ϕ16 ϕ6/300mm 		COLUMN 350x700mm A_s=8 ϕ18 ϕ6/300mm 	

3.2 Effect of tsunami-induced vertical loads

An incremental analysis has been performed for vertical loads only on the three case study RC frames; the loads are calculated according the two aforementioned load combinations provided by the ASCE 7-16 Standard. For this preliminary simulation, it is assumed that the external infills break away for a tsunami inundation depth equal to 1.6m from the lower edge of the infill panel. The VDPO2 analysis with only vertical loads is performed up to a maximum tsunami inundation depth of 6m, i.e. the second storey of the frames is reached. The axial load variation in first storey interior and exterior columns is plotted as a function of the tsunami inundation depth in Fig.2 for the frames. Neglecting the effects of horizontal loads that induce a compression/decompression of frame columns, the following can be highlighted with relation to the 4 phases of analysis described in Fig.1:

(1) During Phase 1, the axial load in first storey columns is constant and given only by gravity loads until the creation of air pockets below the first storey slab;

(2) In Phase 2, it is assumed that the air pockets induce a constant uplift pressure on the first storey slab as given by Eq. (1), causing a reduction of compressive axial load in ground storey columns;

(3) In Phase 3, the axial load is further reduced by buoyancy caused by the enclosed space at the first storey (Fig.2c). This reduction in axial load increases linearly with the tsunami inundation depth until the out-of-plane failure of the first storey infills (at H_w = 4.6m based on the previous assumption that infills break away for a tsunami inundation depth equal to 1.6m from the lower edge of the infill panel);

(4) In Phase 4, after the out-of-plane collapse of the first storey infills, the buoyancy caused by the enclosed space is replaced by the buoyancy caused by the submerged structural members, in addition to the uplift due to the air pockets below first storey slab. The axial load increases but a net reduction with respect to the Phase 1 axial loads is present, as would be expected;

(5*) when the tsunami inundation depth achieves the lower edge of the second storey beams, air pockets are entrapped below the second storey slab inducing an additional uplift pressure on it.

Though the analysis is stopped at Hw=6m, it is clear that if the inundation depth were increased, a similar pattern of axial load reduction and partial recovery as in (1) to (5*) would continue as further storeys are sequentially inundated, resulting in further net loss in axial load with respect to “dry” condition.

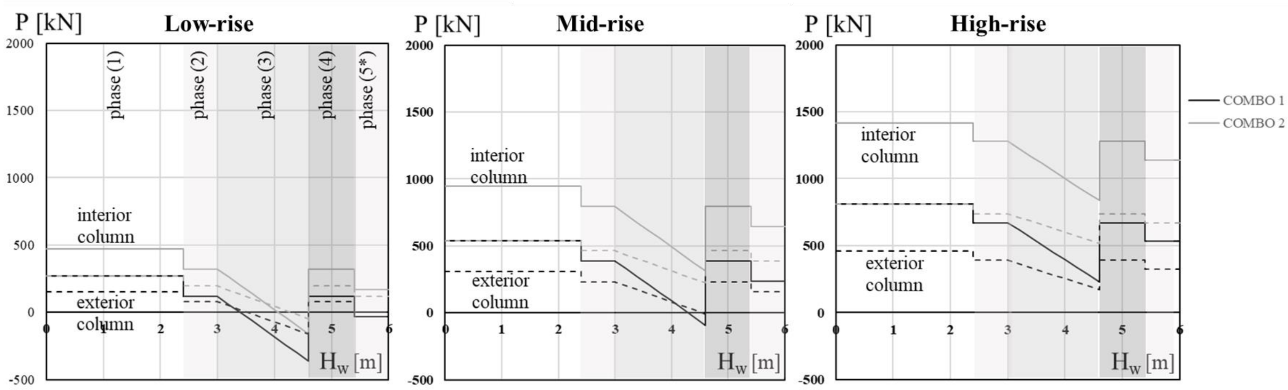


Fig. 2 – Axial load in ground-storey columns as a function of the tsunami inundation depth for low-rise, mid-rise and high-rise case-study RC frames. The results are shown for the two load combinations defined in ASCE7-16, see Eq.(2).

It is observed that the buoyancy due to enclosed space causes a strong axial load reduction on the ground storey column, especially for the low-rise RC frame, where the columns undergo tensile axial loads between the tsunami inundation depths of 3.4m and 4.6m. The buoyancy due to enclosed space is a function of the out-of-plane capacity of external infills. Hence, the greater the inundation depth required to break the infills (i.e. the stronger the infills are in the out-of-plane direction), the higher the uplift pressure on slabs due to buoyancy.

To further investigate the effects of vertical loads on the structural capacity of RC frames, the reduction of flexural capacity associated with the axial load variation in ground storey columns is analysed. In Fig.3, the axial load – bending moment (P-M) interaction domain is plotted for the interior ground-storey column of the low-rise case study RC frame, along with the range of axial load variation for the two load combinations suggested by the ASCE 7-16 Standard. The minimum value of external axial load, P_{min}, recorded during the VDPO2 corresponds to the condition of maximum uplift pressure on first storey slab due to air pocketing and buoyancy (Phase 3).

The maximum flexural capacity reduction is calculated as the ratio between the flexural capacity under gravity loads, $M\_P_{gravity}$, and the flexural capacity under P_{min}, M_P_{min}, for the two load combinations suggested by the ASCE 7-16 Standard and summarized in Table 2. As expected, it is observed that the low and mid-rise frames are more sensitive to the tsunami-induced vertical loads compared to the high-rise frame, with flexural capacity reduction up to 100% in COMBO 1 and 73% in COMBO 2.

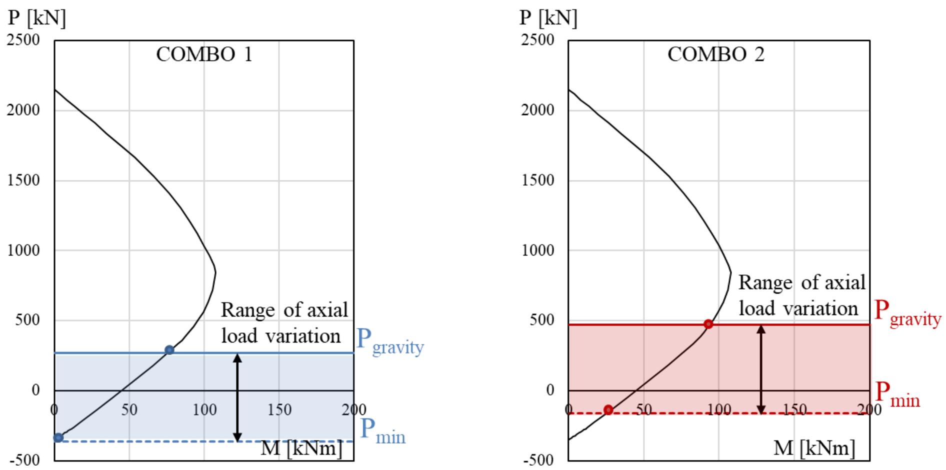


Fig. 3 – Axial load variation in ground storey interior columns on P-M interaction domains for the low-rise RC frame.

Table 2 – Flexural capacity reduction due to axial load variation in interior ground storey columns

Case study RC frame		Low-rise		Mid-rise		High-rise	
Load Combination		COMBO 1	COMBO 2	COMBO 1	COMBO 2	COMBO 1	COMBO 2
$M\_P_{gravity}$	[kNm]	76	94	254	298	462	549
M_P_{min}	[kNm]	0	25	121	213	320	468
Capacity Reduction ΔM	[-]	**100%**	**73%**	**52%**	**29%**	**31%**	**15%**

In terms of shear capacity, according to current models provided by the US code ACI 369 [8] and the European code EC8-3 [9], if a column is under tension then the arch effect given by the axial load should be neglected from the calculation of its shear capacity. The effect of axial load variation on the shear capacity of ground storey interior columns of the low-rise case study frame is depicted in Fig.4 for both load combinations of ASCE 7-16 (see Eq.(2)). The shear capacity (V_{RD}) is calculated according to the models provided by ACI 369 and EC8-3. A strong reduction in shear capacity with respect to the gravity load condition is associated with the axial load variation caused by the tsunami-induced vertical loads. This reduction ranges between 21-28% and 40-50% for the V_{RD} calculated according to ACI 369 and EC8-3, respectively. Thus, this effect should be considered during the design/assessment of structures in order to avoid unexpected brittle failures.

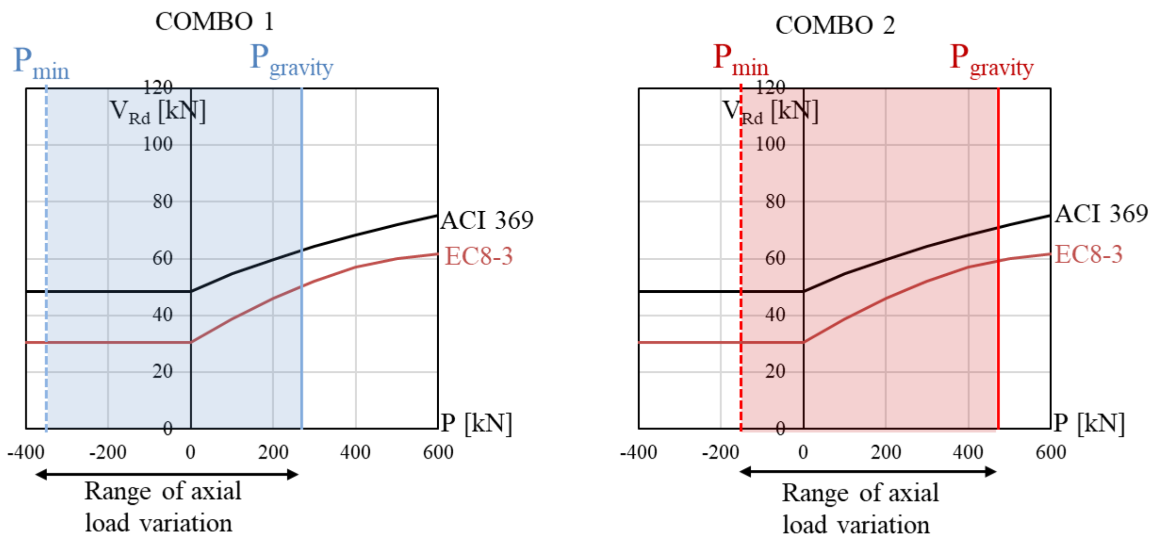


Fig. 4 – Tsunami-induced axial load variation in ground storey interior columns plotted with respect to the V_{Rd} – P interaction domain for the two load combinations of ASCE 7-16.

4. Conclusions

In the present work, the tsunami-induced vertical loads as defined by the ASCE 7-16 Standards have been presented and applied to three case study reinforced concrete frames with breakaway infills, representative of low, mid and high-rise existing buildings of the Mediterranean area. For this analysis, the vertical loads are applied incrementally, simulating the stages of tsunami inundation of the frames and sequential submergence of upper stories as the inundation depth increases, in accordance with the VDPO2 approach. The resulting axial load variation caused by vertical loads on the ground-storey columns of the frames are evaluated for the two load combinations suggested by ASCE 7-16.

The results show that the tsunami-induced vertical loads lead to a significant decompression of ground storey columns. Tensile axial loads in these columns is achieved in the low-rise and mid-rise RC frames when the first-storey of the frames is submerged by the tsunami inundation. It is observed that the out-of-plane capacity of external infills in the upper storeys of the frame have a direct impact on the buoyancy developed, with stronger infills resulting in higher uplift pressures on slabs.

The reduction in axial loads in columns causes a strong reduction in both flexural and shear capacity of members with respect to the gravity load condition, leading to a premature failure than would not be expected considering gravity loads only. Therefore, this preliminary study indicates that tsunami-induced vertical load components should be explicitly considered in the ASCE 7 tsunami structural analysis methodology for the design and assessment of tsunami evacuation buildings.

5. Acknowledgements

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