Assessing the effect of tsunami-induced vertical loads on RC frames

Marta Del Zoppo[a], Tiziana Rossetto[b], Marco Di Ludovico[a], Andrea Prota[a]

[a]*Department of Structures for Engineering and Architecture,*
University of Naples Federico II,
Via Claudio 21, Naples 80129, Italy

[b]*EPICentre, Department of Civil, Environmental & Geomatic Engineering,*
University College London,
Gower Street, London WC1E 6BT, United Kingdom

Abstract
The increasing number of people, structures and economic activities being exposed to tsunami hazards makes it important to estimate the effects of this hazard on coastal developments. Tsunami onshore flow generates significant loading on buildings and infrastructure, which can lead to structural failure. Literature works recently proposed a non-linear static analysis method, called Variable Depth Pushover (VDPO), for assessing the performance of buildings under the lateral pressures induced by a tsunami onshore flow. This methodology was developed under the assumption that the building is watertight. However, in the case of buildings with breakaway cladding (e.g., masonry infills), the water flow passing through the building induces vertical loads on horizontal structural members, due to uplift and buoyancy pressures, that should be considered during the analysis. Thus, to address this phenomenon, in this paper a numerical investigation is performed considering a combination of tsunami-induced horizontal and vertical loads on a case-study reinforced concrete (RC) moment-resisting frame with breakaway infills, typical of Mediterranean construction. The building model is subjected to a VDPO analysis that applies different types and sizes of vertical loading on the horizontal elements of the building, as the tsunami inundation depth increases. From the results of this analysis, the effects of tsunami-induced vertical load components on the case-study building in terms of damage propagation and failure mode are discussed, and the significance of considering vertical loading is proven.

1 Introduction

Recent devastating earthquake-triggered tsunami events (Indian Ocean 2004, Chile 2010, Great East Japan 2011) tested the resilience of coastal communities to this natural hazard. In particular, the Great East Japan tsunami 2011 highlighted how even well-constructed seismically designed reinforced concrete (RC) structures could suffer collapse in a tsunami event [1]. The need to ensure safe vertical evacuation shelters for coastal populations in areas at risk from tsunami leads to the definition of performance-based methodologies able to assess with sufficient accuracy the capacity of buildings subjected to tsunami inundation.

Only few existing studies have proposed numerical tools for assessing the capacity or the fragility of structures under tsunami onshore flows [2-4]. One such tool is the nonlinear static procedure named Variable Depth Pushover, VDPO, recently been proposed in Petrone et al. 2017 [5] and improved in Baiguera et al. 2019 [6] to be compatible with the provisions of the ASCE 7-16 Standard [7], (i.e. VDPO2). To date, VDPO has been used for assessing the performance of watertight buildings, considering only tsunami-induced horizontal loads distributed along the seaward columns. However, in the case of buildings with breakaway infills or openings, the tsunami flow induces vertical loads on structural elements. These vertical forces have largely been ignored in existing studies investigating the tsunami capacity or fragility of buildings.

This paper first gives an overview of the vertical loads induced by a tsunami flow, as per the ASCE 7-16 Standard. A new procedure for the tsunami assessment of buildings with openings or breakaway infills is then proposed. This proposed procedure explicitly integrates step-by-step the tsunami-induced vertical loads acting on structural members in the VDPO incremental analysis, i.e. both horizontal and vertical loads are applied to the structure in increasing increments once the inundation depth reaches the first-floor beams. The modified VDPO is applied to a case study RC frame representative of lowrise existing buildings in the Mediterranean area to point out the effects of vertical loads on local and global behaviour of the structure. The paper closes with a discussion of the importance of including the vertical loads in a tsunami structural analysis.

2 Tsunami-induced loads on structures

Tsunami onshore flows induce a complex combination of time-varying horizontal and vertical loads on structures [1]. Horizontal loads mainly consist of hydrostatic pressure, hydrodynamic or drag pressure, impulsive or bore forces and debris impact loads. Conversely, vertical loads are related to hydrostatic buoyancy and hydrodynamic uplift [7, 8]. Several experimental studies have been conducted for the definition of equations to predict the pressure induced by quasi-steady tsunami inundation flows on watertight buildings [9, 10], and represent a reliable alternative to code equations. Conversely, few experimental simulations have been performed with the purpose of quantifying vertical tsunami loads acting on structural members in buildings with openings or breakaway infills [11]. Due to the lack of experimentally validated equations for quantifying the vertical loads acting on structural members, in this work these loads are defined according to the American Standard ASCE 7-16 for the design of tsunami vertical evacuation buildings.

2.1 Horizontal loads

In accordance with the VDPO approach of Petrone et al. [5], the experimental-analytical research equation by Qi et al. [7] is employed for assessing the drag force acting on a rectangular building impinged by a tsunami onshore flow. The equation considers two different flow regimes that can occur for a steady-state flow impacting an obstacle (i.e. subcritical and choked). The transition between the two regimes is determined by a critical value of the Froude number that is defined in the paper. The Froude number is defined as $Fr = u/\sqrt{gH_w}$, where u is the flow velocity and g is the acceleration of gravity. As the Froude number increases, a hydraulic jump downstream of the obstacle is observed and the flow condition turns from subcritical to choked (supercritical). The tsunami force per unit structural width (F) can be estimated as:

$$F = 0.5 C_D \rho u^2 hb \qquad \textit{subcritical flow regime} \tag{1}$$

$$F = \lambda \rho g^{1/3} u^{4/3} h^{4/3} \qquad \textit{chocked flow regime} \tag{2}$$

where C_D is a drag coefficient, ρ is the sea water density, H_w the inundation depth, λ is the leading coefficient, and *Fr* is the Froude number. More details about the model can be found in [5]. The above-mentioned equation allows to estimate the tsunami force as a function of flow velocity and inundation depth. The net force given by Equation (1) or (2) is then applied on the frame assuming a triangular lateral pressure.

2.2 Vertical loads

According to the ASCE 7-16 Standard, a tsunami induces vertical pressures on the horizontal members of a building with openings (opening ratio > 25%) or with breakaway infills, consisting of hydrostatic and hydrodynamic components. Conversely, in the case of watertight frames, the vertical loads due to buoyancy are hydrostatic in nature and act only at the foundation level, causing a global overturning mechanism. However, these loads are not considered in this paper, due to their strict dependence from the soil-water interaction. The different types and distributions of tsunami-induced vertical pressures are illustrated in Figure 1 for a watertight frame and for a frame with breakaway infills.

In the case of breakaway infills or openings, the hydrostatic vertical loads include:

- **Buoyancy due to air pocketing**: buoyancy should include the effect of air pockets trapped below floors, for instance between consecutive beams and slab in the case of frames (see Figure 1b), computed as in (3):

$$p_{ap} = \gamma_s h_{beam} \tag{3}$$

where h_{beam} is the net height of the beams with respect to the slab.

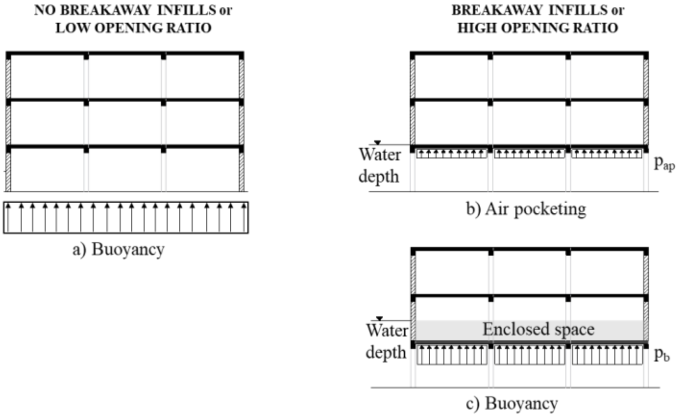


Fig. 1 Tsunami-induced vertical loads on a frame w/o breakaway infills.

- **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 iniflls (or windows) break away (Figure 1c). All windows, except those designed for large missile wind-borne debris impact or blast loading, are considered broken away when the inundation depth reaches the top of the windows or the expected out-of-plane capacity of the windows. The up-lift pressure on slabs due to hydrostatic buoyancy can be computed as in (4):

$$p_b = \gamma_s h^* \tag{4}$$

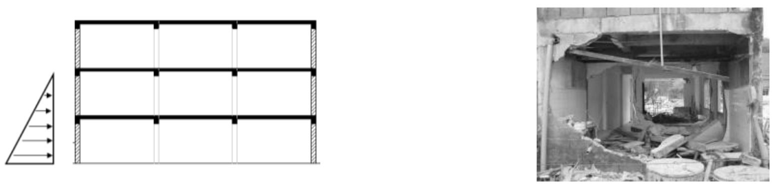
where γ=1127.5 kN/m^3 is the sea water specific weight density, h^* is the height of displaced volume of water (i.e. depth of the enclosed space).

Note that in this 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 such as the velocity or the Froude number.

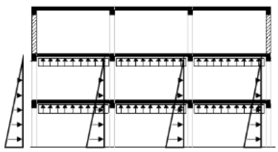
3 Structural analysis methodology

The Variable Depth Pushover (VDPO) has been herein modified to account for the vertical load components induced by tsunami flows on a frame structure. In the VDPO, the tsunami inundation depth (H_w) at the site of the structure is monotonically increased up until structural collapse, with the tsunami-induced loads calculated assuming a constant Froude number. To date, the VDPO methodology has been used for assessing the performance of watertight buildings (Figure 2a), so neglecting the effects of vertical loads induced by the collapse of breakaway claddings or openings.

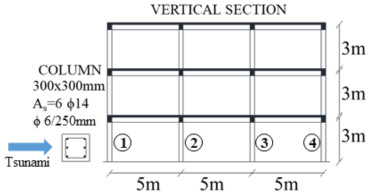
However, post-tsunami surveys reveal that masonry infills are particularly vulnerable to out-of-plane collapse during inundation, see Figure 2b. Thus, the VDPO procedure has been recently implemented to account for the collapse of breakaway infills for increasing tsunami inundation depth [12]. In particular, the analysis checks if the out-of-plane capacity of external infills is achieved at a certain inundation depth (for any constant Froude number). After this inundation depth is reached, the water can pass through the building, inducing horizontal hydrodynamic loads on interior columns, in proportion to their impacting surface (Figure 2c). This leads to a different distribution of actions on structural members with respect to the case in which only the seaward columns carry the horizontal loads.



(a) (b)



c)



(d)

Fig. 2 VDPO for watertight frames (a); out-of-plane collapse of breakaway infills (b); modified VDPO for frames with breakaway infills and vertical loads (c); case-study frame (d).

4 Application to a case study RC frame

To investigate the effects of tsunami-induced vertical loads on buildings, a case study RC frame has been defined and the modified VDPO has been performed with the software OpenSees [13], considering the out-of-plane collapse of breakaway infills.

4.1 Case study building

The case study building is a three-storey and three-bay RC 2D frame, that has been designed for gravity loads only according to the allowable stress method. As such, it is representative of buildings built before the 1980s in the Mediterranean coastal area. The building has an interstorey height, *h*, of 3m and bay span, *L*, of 5m. The first-storey columns have a 300x300mm cross-section with a longitudinal reinforcement consisting of 6 ϕ14 bars. The transverse reinforcement consists of ϕ6 bars spaced at 250mmand beams have a 300x500mm cross-section, according to the strong beam-weak column hierarchy typical of existing structures. The masonry panel orthogonal to the flow direction has a length of 5m and a thickness of 180mm. Details of the case-study are shown in Figure 2d.

Dead and live loads were considered equal to 4.5 kN/m^2 and 3 kN/m^2, respectively. A concrete compressive strength of 25 MPa and a steel with 450 MPa yield strength were selected for the design of case study building. The frame is modelled using force-based nonlinear beam-column elements, assuming five integration points. Cross-sections are modelled by means of a fibre approach. The stress–strain relationship Concrete04 in OpenSees is used for both unconfined and confined concrete, whereas a bilinear stress-strain envelope, Steel02 in OpenSees, is adopted for the steel reinforcement.

4.2 Watertight frame Vs. frame with breakaway infills

The behaviour of the case study building with breakaway infills is assessed using the modified VDPO with vertical loads (Figure 2c) and is compared with the performance of the same frame, assumed as watertight. The buoyancy pressure at foundation level is assumed to be negligible in the VDPO procedure for watertight buildings, and only the loads acting on the upper structure are considered. In the VDPO analysis, the gravity loads are considered as 0.9 of the dead loads only, according to the load combination suggested by the ASCE 7-16 Standard.

The inundation depth causing the out-of-plane collapse of the infill panel has been calculated following the Dawe and Seah [14] approach and is equal to 1.0 m for a Froude number, Fr = 1. The Fr number value is typical of tsunami onshore flows, and has been assumed in order to demonstrate the methodology. Ideally the Fr number should be derived from simulations of tsunami inundation scenarios.

Figure 3 shows the structural response obtained from the VDPO analysis for the watertight frame (blue line) and the same frame with breakaway infills with (black solid line) and without tsunami-induced vertical loads (red dashed line). The building response is plotted in terms of base shear, *F*, and top displacement, *d*, in Figure 3a, and in terms of tsunami inundation depth, H_w, and interstorey drift ratio for the first storey, *IDR*, in Fig. 3b. The achievement of the first yielding and of the shear failure for first storey columns is also shown on the response curves depicted in Figure 3. The inundation depths and interstorey drift ratios corresponding to such mechanisms are summarized in Table 1, along with the global failure mechanism. The yield point is calculated based on moment-drift relationships for the base cross-section of the first storey columns (Figure 5). It is defined as the intersection point between the secant at the 70% of the peak strength and the horizontal at the peak strength. The shear capacity has been checked at each step of the modified VDPO analysis for the case-study frame according the Eurocode 8-part 3 shear capacity model [15].

It is observed that the watertight frame and the frame with breakaway infills (without vertical loads) achieved the same peak capacity, in terms of base shear, indicating that the same failure mechanism occurred. However, in term of maximum inundation depth, the tsunami force causing the achievement of peak capacity for the watertight frame is associated with a lower inundation depth than that needed for the frame with breakaway infills. This is due to the reduction of impacting surface after the out-of-plane failure of external claddings. The effect of vertical loads on the overall structural capacity is clearly visible when the inundation depth surpasses the first storey (H_w > 3m) and the vertical loads due to air pocketing and buoyancy are applied to the structure. These cause a reduction of yielding and peak capacity with respect to the case without vertical loads.

All models achieved the premature shear failure of the exterior column 1 before first yielding. Note that, in the case of watertight frame, the shear failure of the column is achieved for an inundation depth of 1.7m. Conversely, in the case of breakaway infills, the shear failure occurred after the out-of-plane failure of infills (occurring for an inundation depth of 1m) for inundation depths of 3m and 3.4m, respectively with and without considering the vertical loads (see Table 1).

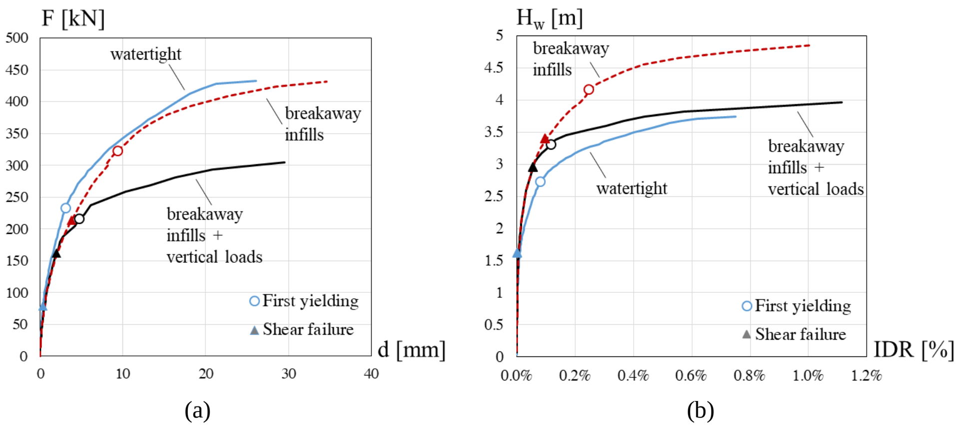


Fig. 3 Performance curves from VDPO for the case-study frame: base shear F – top displacement d (a) and inundation depth H_w – interstorey drift ratio IDR (b)

Table 1 Damage mechanisms.

Case study	Global failure			First yielding			Shear		
	F	H_w	IDR	F	H_w	IDR	F	H_w	IDR
	kN	m	%	kN	m	%	kN	m	%
Watertight	432	3.7	0.75%	233	2.7	0.08%	78	1.7	0.01%
Breakaway infills + vertical loads	305	4.0	1.11%	216	3.3	0.12%	163	3.0	0.05%
Breakaway infills	432	4.9	1.01%	323	4.2	0.25%	214	3.4	0.10%

To better understand the global structural behaviour, the axial load *P* acting on first storey columns 1 (exterior column) and 2 (interior column) is plotted in Figure 4 for the watertight frame and the frame with breakaway infills and vertical loads. The buoyancy due to the air pockets causes a sudden drop in the external axial load (see Figure 1a). The axial load is further reduced by the uplift pressure on first storey slab caused by buoyancy, induced by the enclosed space in the partially submerged building before the external infills break away (see Figure 1b). This causes a high reduction of compressive axial load in columns, up to negative values (i.e. tension).

To understand the failure mechanism that caused the achievement of flexural peak capacity (Figure 3), the flexural responses of cross-sections at the bottom of first storey columns are depicted in Figure 5, ignoring the shear interaction. The plots show the relation between bending moment at the bottom of columns, *M*, and the interstorey drift ratio at first storey, *IDR*.

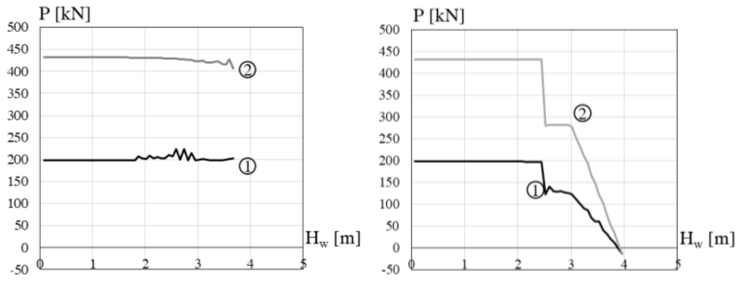


Fig. 4 Axial load variation from VDPO for (a) watertight frame and (b) frame with breakaway infills and tsunami-induced vertical loads.

It is observed that, in the case of the watertight frame, column 1 develops large inelastic deformations at the bottom cross-section, whereas the other columns achieve yielding just before global failure, (associated with a soft storey mechanism, Figure 5a). This is mainly related to the load condition, where the lateral load is applied to the seaward column only, causing possible local failures due to the exceedance of member's deformation capacity before the achievement of the soft-storey mechanism [12].

Conversely, in the case of frame with breakaway infills, the yielding is achieved at the bottom of all first storey columns almost at the same time, leading to a soft-storey failure mechanism (Figure 5b-c). The axial load reduction induced by vertical loads clearly causes a significant reduction in the cross-section bending capacity, leading to a reduced base shear.

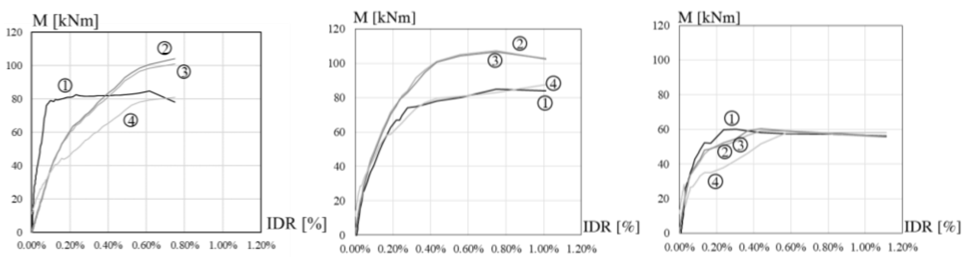


Fig. 5 Moment-IDR relationship at bottom of first storey columns from VDPO for (a) watertight frame, (b) frame with breakaway infills, (c) frame with breakaway infills and vertical loads.

5 Conclusions

The present work integrated the tsunami-induced vertical loads in the VDPO nonlinear static analysis to understand their effects on the behaviour of RC frames with breakaway infills, typical of Mediterranean coastal regions. The tsunami-induced vertical loads are first presented as defined by the ASCE 7-16 Standards. Then, a modified VDPO methodology for frames with breakaway infills is illustrated and the procedure for integrating vertical loads in the incremental analysis is discussed.

The effects of vertical loads on the overall structural behaviour and on the local failure mechanisms are investigated on a case-study RC frame, designed for gravity loads and representative of existing buildings in southern Europe. The analyses show that the axial load reduction caused by the tsunami-induced vertical loads strongly affects the capacity of the structure at a global and local level. Neglecting the vertical load components induced by a tsunami onshore flow can lead to an overestimation of the actual capacity of the frames with breakaway infills. The results also showed that the shear failure is a predominant local failure mechanism for first storey columns, and the axial load reduction leads to a premature achievement of such brittle failure. More experimental and numerical investigations about the modelling of tsunami-induced vertical loads on structures are required to further develop the methodology.

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