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TSUNAMI ANALYSIS OF STRUCTURES: COMPARISON AMONG DIFFERENT APPROACHES

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Abstract

The widespread damage caused by past tsunami, e.g. 2004 Indian Ocean Tsunami and 2011 Great East Japan tsunami, has motivated several research activities in tsunami engineering. The behaviour of buildings subjected to tsunami actions has received particular attention. Some studies have been published regarding the estimation of tsunami action; many papers, as well as existing building codes suggest modelling the tsunami-structure interaction with an equivalent force approach. These literature papers propose that the tsunami force and its distribution along the height of the structure are strictly related to the features of the tsunami flow, e.g. flow velocity and inundation depth. However, there is a lack of published literature concerning the analysis methodologies to adopt for estimating the response of buildings to these tsunami loads. A question therefore arises as to which analysis method is the most appropriate in the case of tsunami inundation of buildings and whether the nonlinear static analysis method, commonly used in earthquake engineering, is suitable for this case.

This paper presents a study aimed at shedding light on analysing buildings subjected to actions due to tsunami inundation. In particular, three different analysis methodologies of constant-height pushover (CHPO), variable-height pushover (VHPO), and time-history (TH) analyses are compared in terms of their abilities to predict structural response. An existing 10-storey reinforced concrete tsunami evacuation building in Japan is considered as case study. A distributed plasticity approach is adopted to model the RC frame structure. Two different load patterns, i.e. triangular and trapezoidal, are adopted to distribute the tsunami force along the height of the structure. The two pushover analysis methodologies, i.e. CHPO and VHPO, are compared to TH analysis in terms of their abilities to predict structural response for an extensive set of simulated tsunami inundation time-histories. It is found that the results of VHPO provide a good prediction of the engineering demand parameters obtained from the TH analysis under a wide range of tsunami time-histories. CHPO gives a worse prediction of the demand; it overestimates interstorey drift ratio and underestimates column shear by about 5-20%. It is concluded that pushover methods are a good proxy for TH. In particular, it is recommended that VHPO be used in future analysis of buildings subjected to tsunami. It should be also highlighted that pushover methods may be inadequate in cases where the tsunami inundation force time-history is characterised by a double-peak, which subjects the structure to a two-cycle load.

Keywords: tsunami; structural analysis; dynamic analysis; static analysis; fragility

1. Introduction

Recent tsunami events (e.g. 2004 Indian Ocean tsunami and 2011 Great East Japan tsunami) have caused numerous deaths and widespread damage. The 2004 Indian Ocean tsunami caused 230,000 deaths [1], whereas the 2011 Great East Japan (Tohoku) earthquake-tsunami caused 19,000 fatalities [2]. In the 2011 Tohoku event, US$211 billion direct loss was estimated [2]. It is worth noting that such a loss does not include indirect losses, such as supply-chain disruptions and retail trade and tourism reduction due to restrained consumption and radiation fears.

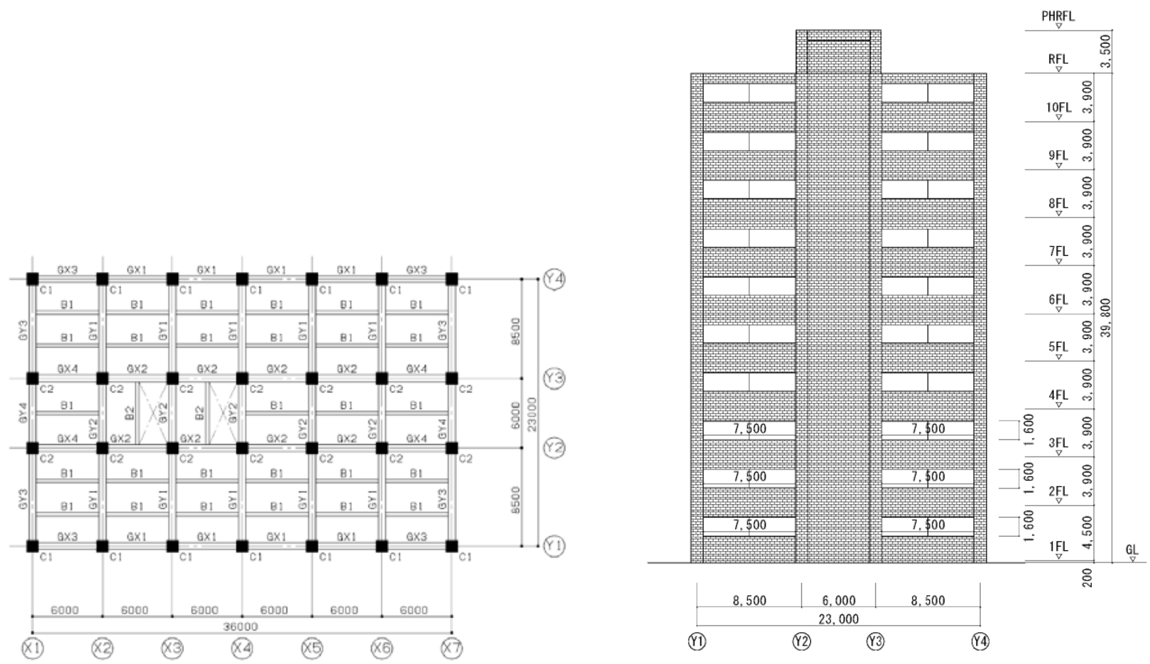
These observed impacts from tsunami can only be reduced through the development of comprehensive mitigation plans based on tsunami impact scenarios and risk assessments. An important component in the evaluation of tsunami impact or risk is the estimation of building fragility due to tsunami onshore flow. This has recently been recognised by researchers worldwide [3; 4; 5]. To date the majority of this research has focussed on the development of fragility functions based on observational post-tsunami damage data, in particular after the 2004 Indian Ocean tsunami (e.g. [6; 7]) and the 2011 Japan tsunami (e.g.[5]). Empirical tsunami fragility functions are by their nature specific to the event represented in the post-event damage data as well as the local building stock, and suffer from typical absence of locally recorded tsunami intensity measures (IMs). Tsunami inundation depths can be obtained from the inspection of water marks on standing buildings, whereas other IMs, such as flow velocity, is difficult to assess after the event. It is important to recognise that the building damage observation data have been affected by both earthquake and tsunami loads, and implicitly include the response of buildings to the combined hazards. As post-tsunami reconnaissance cannot distinguish damage due to the two hazards, it is difficult to determine whether preceding damage due to the earthquake has affected structural response to the tsunami inundation. The assessment of structural performance through numerical analyses is therefore essential to overcome the mentioned limitations of empirical fragility functions. Analytical fragility functions can also be used together with empirical assessments to provide a deeper understanding of structural behaviour under tsunami actions.

All the existing tsunami analytical fragility studies, e.g. [8; 9; 10] are associated with a number of issues that affect their accuracy. Firstly, the tsunami action is typically modelled with an equivalent force according to design prescriptions, without taking into account realistic tsunami inundation time-histories. Current design building codes might be inadequate in assessing tsunami force; in particular, conservative assumptions are typically made for design purposes. Secondly, gross assumptions are made regarding the pressure distribution along the height of the structure resulting from the tsunami actions, without consideration of the potential sensitivity of the structural response to variations in the pressure distribution or how the load is discretised and applied to the structural model. Thirdly, available studies typically consider only nonlinear static analyses pushing the structure up to the structural peak strength, where the structure cannot be considered to have failed. It is clear that there is a gap in knowledge in determining how tsunami loads should be applied to a building and which analysis methodology is most suitable for the estimation of building response to realistic tsunami.

This paper takes a first step to address these issues by assessing different nonlinear static analyses and comparing them with dynamic analyses performed considering realistic tsunami inundation time-histories. The assessment is performed in terms of the ability of each nonlinear static method to predict the peak structural response observed in the dynamic analyses. Peak structural response, e.g. maximum interstorey drift ratio (IDR), is referred to as "demand" in the following, whereas tsunami peak intensity is expressed in terms of IM, e.g. inundation depth. The study takes advantages of the numerical-experimental studies developed at UCL and HR Wallingford for the assessment of tsunami forces on structures [11; 12]; and extensive tsunami simulations for generating realistic tsunami wave traces [13]. The paper is breakdown into different sections. First, a case study building, a Japanese tsunami evacuation building, is described and then its modelling is discussed. Particular attention is paid to the definition of tsunami load through the adoption and modification of the formulation of Qi et al. [12]. A tsunami inundation simulation of the 2011 Tohoku tsunami is presented in order to define a number of tsunami wave traces in terms of inundation depth and flow velocity, for use in the dynamic analyses of the structural model. Different non-linear static analysis methodologies for the assessment of the building response are defined. The demand on the building, in terms of maximum IDR and shear, is then evaluated using the defined nonlinear static analysis methods and compared to the results of the nonlinear dynamic analysis, with the aim of identifying the bias induced by adopting the former simpler analyses.

2. Methodology

The case study building selected is a tsunami evacuation building, consisting of 10 storeys and RC frames in both horizontal directions (Fig. 1). Building plan dimensions are 36×23 m, with a constant 3.9 m interstorey height for all storeys except for the ground storey, which is 4.5 m high. Six and three bays can be identified along the longitudinal and transverse directions, respectively. The tsunami evacuation building is taken from the design example 3-1 of the "structural design and members section case studies" [14]. The structure is also designed to resist tsunami loads, assuming a 10 m inundation depth and coefficient α equal to 2.0, yielding an effective inundation equal to 20 m in calculating the wave forces action the building. However, the tsunami design is conducted assuming that the first two floors are “pilotis”, i.e. do not have infills. This research study neglects the presence of openings; it is assumed that water flow is obstructed in all bays for the whole height of the structure. Such an assumption causes an increase in tsunami force and allows the investigation of a more common case, where infill walls are installed throughout the height of the structure. Further details on the case-study structure are included in [15].



(a) (b)

Fig. 1 - Case study structure: (a) plan view and (b) lateral view [14]

The case study building is modelled within an OpenSees platform [18]. A 2D model of a transversal frame of the structure is considered, as its behaviour is assumed to be representative of the whole structure since all transverse frames are identical. One seventh of the seismic mass of the corresponding 3D building is assigned to a master joint at each floor. A distributed plasticity approach is adopted for the RC frame model. Each element is modelled with a force-based nonlinear beam-column element, assuming five integration points. Cross-sections are modelled by means of a fibre approach. Three different constitutive laws are defined to model column cross-sections: (a) unconfined concrete is associated to cover fibres; (b) confined concrete is associated to core fibres; and (c) steel material is linked to steel discrete fibres. The stress–strain relationship proposed by [19], i.e. Concrete04 in OpenSees, is selected for both unconfined and confined concrete, whereas a bilinear stress-strain envelope with a smooth transition from elastic to plastic branches, i.e. Steel02 in OpenSees, is adopted for steel. Mean strength of steel and unconfined material are assessed assuming the coefficient of variation of 5% and 10% for steel and concrete, respectively [16]. The structural model exhibits a fundamental vibration period of 0.73s.

Tsunami action on the structure is estimated with an equivalent force approach, as suggested in current design guidelines for tsunami resistant structures [17]: tsunami action on building is modelled through a lateral force, which is caused by the fluid-structure interaction. An existing experimental-analytical research study by [12] is employed for this purpose. The study assesses the drag force acting on a rectangular building placed in a free-surface channel flow; the formulation is experimentally validated. Qi et al. (2014) demonstrate that two different flow regimes can occur for a given inlet steady-state flow impacting an obstacle: subcritical and choked. The transition between the two regimes is determined by the Froude number of the impacting flow. As the Froude number increases, a hydraulic jump is observed in downstream of the obstacle and the flow condition turns from subcritical into choked. It is found that the blocking ratio, i.e. the ratio between building width b and flume width w, influences the Froude number threshold between the two regimes. According to [12], the tsunami force per unit structural width can be estimated as follows:

$$F/b = sgn(u)\begin{cases} 0.5C_D\rho u^2 h & \text{if } Fr < Fr_c \\ \lambda\rho g^{1/3}u^{4/3}h^{4/3} & \text{if } Fr \geq Fr_c \end{cases} \tag{1}$$

where $sgn(u)$ is the sign function of the flow velocity, C_D is a drag coefficient, ρ is the density of the fluid assumed $1.20t/m^3$, u is the flow velocity, h is the inundation depth, λ is the leading coefficient, g is the acceleration of gravity, and $Fr = u/\sqrt{g \cdot h}$ is the Froude number. The Froude number threshold Fr_c is estimated from Qi et al. [12]:

$$\left(1-\frac{C_H b}{w}\right)\frac{1}{2Fr_c^{4/3}} + \left(1-\frac{C_D b}{2w}\right)Fr_c^{2/3} = \left(1-\frac{C_H b}{w}\right)\frac{1}{2Fr_{d,c}^{4/3}} + Fr_{d,c}^{2/3};\, Fr_{d,c} = \left(1-\frac{C_H b}{w}\right)^{1/2} \tag{2}$$

where C_H is experimentally calibrated to the value of 0.58 and $Fr_{d,c}$ is the Froude number at the back of the building in a critical condition, i.e. when the flow turns into choked. The drag and leading coefficients are a function of the blocking ratio b/w and can be estimated as in Qi et al. (2014), where C_{D0} can be assumed equal to 1.9. Different blocking ratios can be assumed. For this specific study, b/w is set equal to 0.1, considering a sparse built environment. Tsunami force F is evaluated assuming a 6 m influence width b, equal to the spacing among transversal frames (Fig. 1). The above mentioned formulation allows estimating tsunami force from two input parameters: flow velocity and inundation depth. For a given tsunami inundation flow time-history, the formulation can be applied at each time step in order to assess tsunami force time-history. To avoid discontinuities in force time-histories as the flow state goes from subcritical to choked and vice versa, a smoothing function is proposed to be applied to the $C_D - Fr$ function, as detailed in [15]. Qi et al. [12] focuses on the assessment of net flow force. As the slope of such a pressure distribution is unknown, it is decided to consider two different load patterns representative of extreme cases: (i) a triangular load pattern, which assumes that pressure distributions at the front and at the back are characterised by different slopes with the same water depth; (ii) a trapezoidal load pattern, which assumes that pressure distributions at the front and at the back are characterised by the same slope with different water depths.

Tsunami wave simulation is required in order to assess the impact on the case study structure due to a realistic tsunami (Fig. 2). Goda et al. [13] have generated numerous tsunami wave traces for the 2011 Tohoku tsunami. Tsunami inundation is estimated in terms of inundation depth and flow velocity by evaluating nonlinear shallow water equations considering run-up [18]. The information on bathymetry, surface roughness, and coastal defence structures, is obtained from the Miyagi prefectural government, Japan Hydrographic Association and Geospatial Information Authority of Japan. The bottom friction is evaluated using Manning's formula. Computational cells include those on land, and coastal defence structures are taken into account using an overflowing formula. The initial water displacement caused by earthquake rupture is assessed according to [19] and [20]. Tsunami simulations are performed considering four nested domains (1350-m – 450-m – 150-m – 50-m) and wave-propagation duration of 2 hours with a 0.5s integration time step.

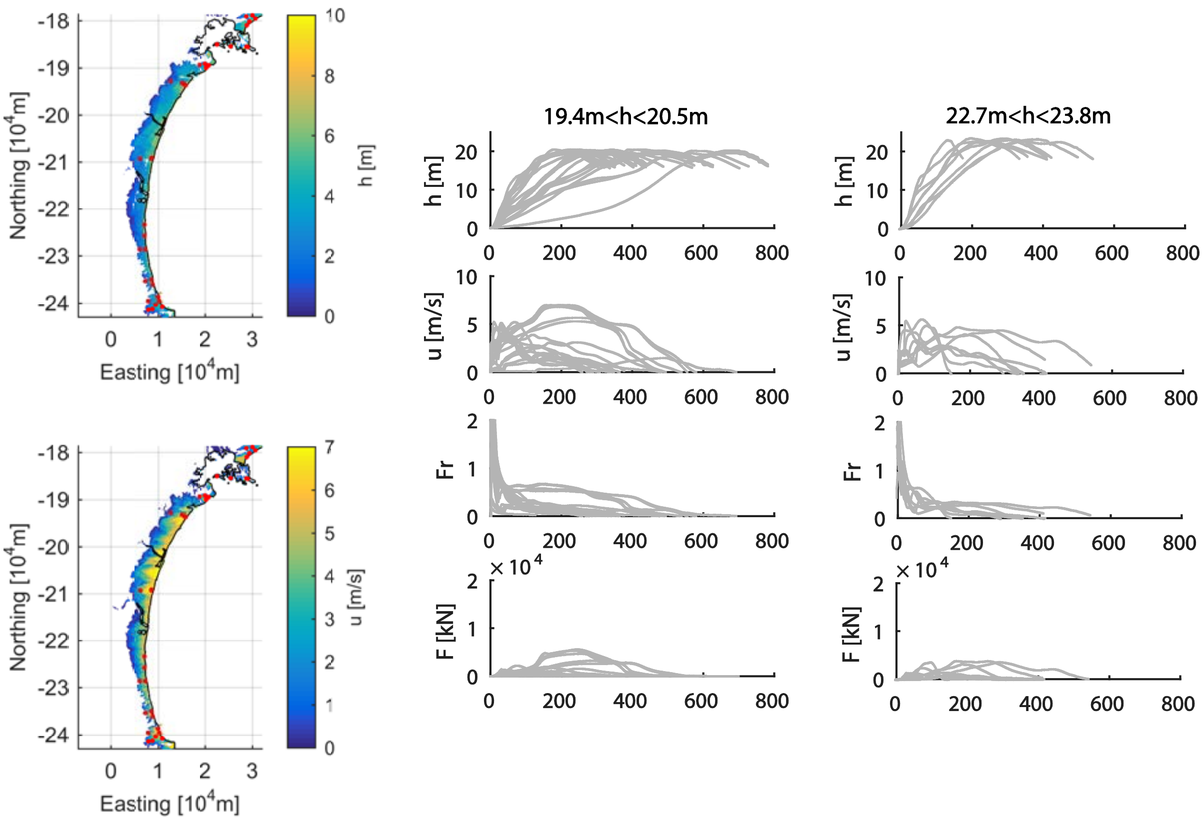


Fig. 2 - Tsunami simulation results and tsunami load assessment. The two figures on the left denote the maximum inundation height *h* and flow velocity *u*, as well as some locations where tsunami traces are computed (red dots). The time histories on the right highlight the force assessment for tsunami wave traces corresponding to two different ranges of maximum inundation depth.

Tsunami simulation is performed considering different slip distributions along the fault. The slip distribution by Satake et al. [21], which was inferred from tsunami waveform data, was adopted as well as ten different stochastic realisations of such a slip distribution included in [13]. Peak inundation depth and flow velocity can be estimated over wide regions, whereas their time-histories are recorded at specific locations (Fig. 2). In this study, 73 different locations along the Tohoku coastline are considered for the 11 adopted slip distributions, yielding 803 different tsunami wave traces. Tsunami force can be estimated for each tsunami inundation time-history, according to the above mentioned formulation. Note that many of the defined time-histories are discarded as they yield very low tsunami forces, i.e. smaller than 2000kN, which would not cause any damage/nonlinearity in the structure. Finally, 125 tsunami wave time histories are used for the 0.1 blocking ratio.

One of the main aims of the study is the assessment of the most reliable method to evaluate structural performance under tsunami actions. Tsunami structural behaviour can be evaluated by adapting analysis approaches typically used in structural dynamics applications. Here, the case study structure is investigated by means of three different analysis methodologies, which features are summarised in Table 1:

- Time-history analysis considering actual tsunami onshore flow time histories (TH)
- Nonlinear static analysis with constant-height load pattern (CHPO)
- Nonlinear static analysis with variable-height load pattern (VHPO)

In TH, a dynamic time-history analysis is carried out considering the tsunami force estimated from simulated time-histories of tsunami onshore flow according to the formulation presented above. The analysis allows the incorporation of the dynamic behaviour of the structure, a feature regarded to be important in the literature but never to date properly evaluated. Within this paper the analysis used adopts a transient solver to allow for post-peak behaviour of the structure to be investigated.

Tsunami force is influenced by both inundation depth and flow velocity. Several pushover methods can be implemented, assuming some constraints on these two IMs: by increasing the flow velocity and keeping inundation depth constant (CHPO), or by varying the depth and calculating the corresponding flow velocity assuming a constant Froude number (VHPO).

Nonlinear static analysis with the constant-height load pattern (CHPO) assumes a load pattern with a constant inundation depth. Similarly to standard pushover analysis, this analysis method increases the roof displacement stepwise and evaluates the load magnitude required to attain pre-defined displacement demand levels. This methodology is similar to earthquake pushover analysis [22] although it is characterised by a different load pattern. It can be interpreted as an analysis where a constant height load pattern is assumed with a variable flow velocity. This analysis can be exploited to evaluate structural performance for a given flow velocity (or Froude number) and inundation depth. In particular, a performance point, characterised by the force level corresponding to the assumed IMs, is identified on the pushover curve; such a point yields the predicted response of structure, e.g. interstorey drift demand.

Nonlinear static analysis with the variable-height load pattern (VHPO) considers a load pattern characterised by a variable height throughout the analysis. At each analysis step the load pattern height is modified according to the assumed inundation depth and the velocity is calculated assuming a constant Froude number. It is preferred to keep the Froude number constant rather than the flow velocity since it is more realistic to assume that the Froude number is constant for a wide range of inundation depths, as also shown in typical tsunami onshore flow time-histories. While CHPO is displacement-controlled, i.e. roof displacement is increased step-wise, VHPO is force-controlled. This feature might cause numerical convergence issues in VHPO as, for instance, the inability to capture any degrading branch in the pushover curve.

Table 1. Features of the considered analysis methodologies

	CHPO	**VHPO**	**TH**
Inundation depth	Constant	Linearly increasing	Actual
Froude number	Increasing	Constant	Actual
Solver	Static	Static	Dynamic
Integrator	Displacement controlled	Force controlled	Newmark

3. Results and Discussion

A load sensitivity analysis was firstly performed, aiming to assess how to discretise tsunami loads on the modelled structure [15]. Four different discretisation approaches were adopted. It was demonstrated that the tsunami load should be distributed along the height of the structure with a proper discretisation scheme. Of the load discretisation trialled, type C (with five load application points per storey) was seen to provide the best solution. A significant discrepancy in the estimation of the shear demand and the interstorey drift ratio (IDR) is noticed if the forces are applied only at storey level.

The different nonlinear static pushover methods are first compared to each other in terms of their ability to predict the response of the structure under tsunami actions. Then, the time-history analysis results are presented and compared with those resulting from the pushover methods. Observations are made as to the advantages and limitations of the pushover methods in reproducing the building response observed in the time-history analysis. Pushover methods are used to evaluate the response of the reference structure to a given tsunami action. Both triangular and trapezoidal load patterns are considered. For the considered blocking ratio all the considered analyses do not induce the failure of the structure. The influence of the adopted analysis methodology on the collapse assessment in investigated in [15]. For a given load pattern (triangular or trapezoidal) a single VHPO is executed, whereas multiple CHPOs are performed assuming different inundation heights. The comparison is performed considering Fr = 0.60 and the load discretisation mentioned above. A performance point can be estimated for each CHPO as the demand point characterised by the force corresponding to Fr = 0.60. An equivalent VHPO is estimated from CHPO and compared to the VHPO curve (Fig. 3). Particular care is taken in defining different discrete tsunami loads, which reflect both the assumed inundation depth and force amplitude time-histories. For instance, a load at a given height is set to zero until inundation depth exceeds that height. It should be recalled that VHPO analysis is not suitable to investigate post-peak behaviour when the structure exhibits a softening behaviour. The analysis fails to converge as the peak building strength is reached as it is evaluated by a load-control integrator. However, VHPO is considered to be a more refined analysis compared to CHPO, given its more realistic implementation of time-variant tsunami load. VHPO is therefore treated as the reference analysis. The bias induced by the CHPO analysis, which is favoured in the existing literature, is estimated.

Comparison of the CHPO and VHPO pushover curves shows a noticeable mismatch. In particular, CHPO underestimates the peak strength compared to VHPO. This phenomenon can be attributed to the different loading history subjected to column 1011 in the two considered analyses. It is observed that that in this column local nonlinear deformations due to the distributed lateral loading start to accumulate at an earlier stage in VHPO than in CHPO. The accumulation of local nonlinear deformations in column 1011 leads to a more effective restraint provided by the beams at the first storey level in the VHPO case. A more effective restraint causes a larger moment at the top of the column and a smaller shear span ratio at the column base. The peak force, which occurs at the activation of the plastic hinge at the column base, is therefore larger in VHPO as a result of the smaller shear span ratio. The accumulation of local nonlinear deformations in VHPO also increases the stiffness of the structure, as they tend to reduce IDR at the first storey. As a result, top displacement and IDR are overestimated by CHPO, whereas shear can be underestimated (Fig. 4). Discrepancies in IDR are significant particularly close to collapse, due to the different strengths predicted by the two analysis methodologies.

The study then focuses on the comparison of time-history analysis with the pushover methods, in terms of demand on the structure under the tsunami inundation flow. TH analysis is performed by applying 125 tsunami flow time-histories to the case study structure. The response of the structure is assessed by means of CHPO and VHPO for each tsunami inundation trace. The CHPO analysis is performed using the inundation height that occurs at the time step characterised by the peak force of the tsunami wave trace. VHPO analysis assumes that the Froude number equals the value at the peak force time step of the inundation time-history. The structural demand is recorded for each of the 125 tsunami flow traces, characterised by a tsunami IM. This procedure allows the investigation of the behaviour of the structure at different tsunami intensity levels. It is similar to a “cloud” analysis, which is widely used in earthquake engineering [23] to investigate the trend of structural demand at different earthquake intensity levels.

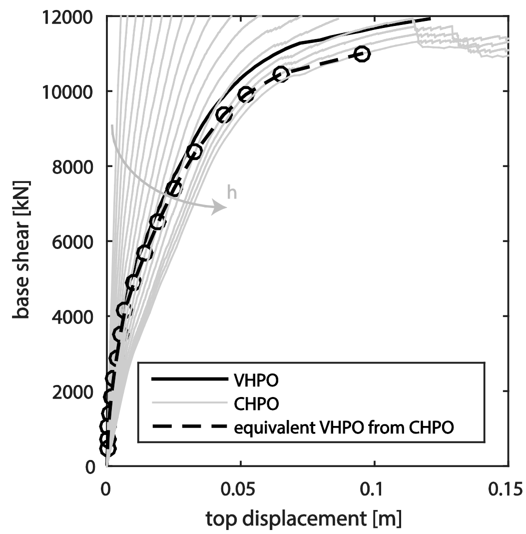
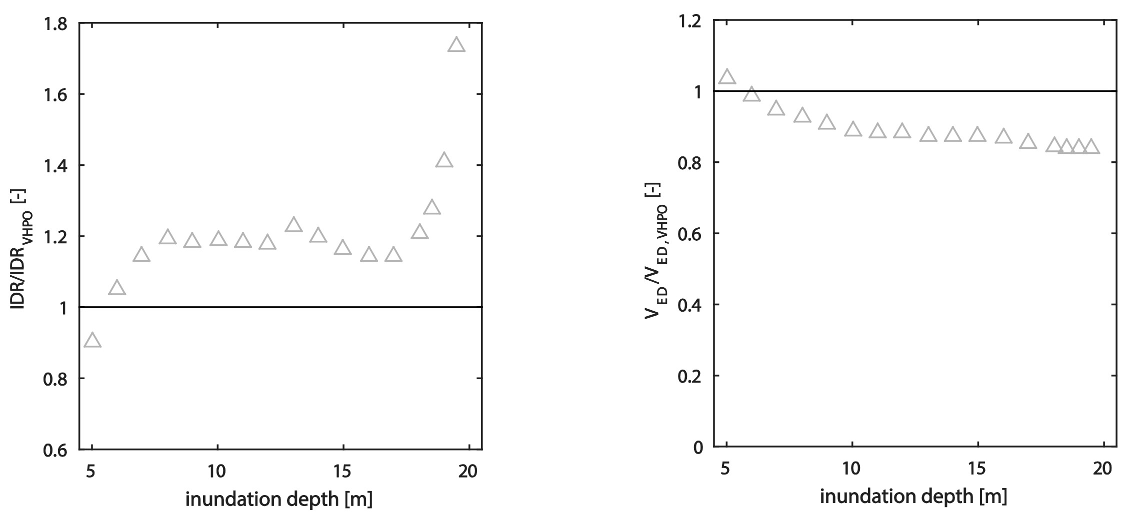


Fig. 3 - Variable height pushover analysis (VHPO) vs constant height pushover analysis (CHPO) for a triangular load pattern. Note that performance points in CHPO are highlighted with black circles



(a) (b)

Fig. 4 - Overestimation of (a) IDR at 1st floor and (b) shear demand in column 1011 due to CHPO

Assessment of the structural demand is straightforward in the TH analysis, whereas it is estimated at the performance point for the pushover analyses. It is worth recalling that the performance point is characterised by the intersection of the pushover curve with a base shear equal to the peak force of the considered tsunami wave trace (Fig. 5). If the latter exceeds the peak strength of the structure predicted by the pushover analysis, the structure is assumed to have collapsed. However, collapse points are not recorded for the considered blocking ratio. The comparison of analyses methods for collapse was performed in [15] in terms of the ability of the methodologies to predict collapse, rather than a specific engineering demand parameter. Overall, up to collapse level, it is observed that the pushover methods give a good prediction of the structural demand when compared to TH (Fig. 5a-b). CHPO tends to slightly overestimate the displacement demand. However, in a few cases a large discrepancy between TH and pushover methods is observed (e.g. Fig. 5c-d). The occurrence of these cases corresponds to cases when the tsunami inundation force time-history is characterised by a double-peak, which subjects the structure to a two-cycle load. The second cycle of the time-history may induce larger displacements than the first cycle, as the structure has already sustained damage due to the first cycle and therefore has a reduced stiffness (as seen in Fig. 5c). Similar conclusions can be drawn in case trapezoidal loads are adopted. In such a case the inundation depth, which causes the structure to fail, is slightly smaller. This phenomenon is due to the larger lever arm which characterises trapezoidal loads.

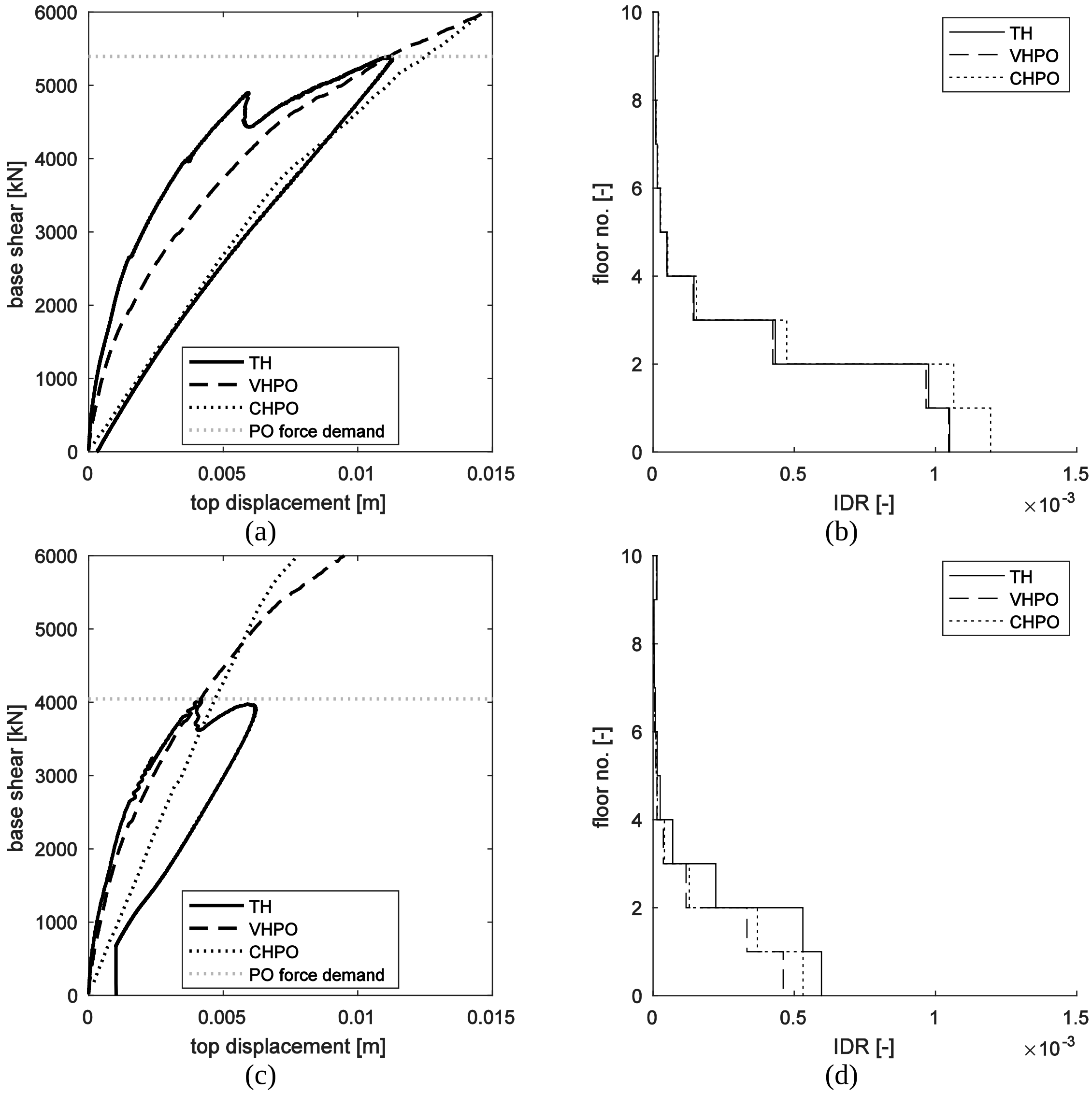
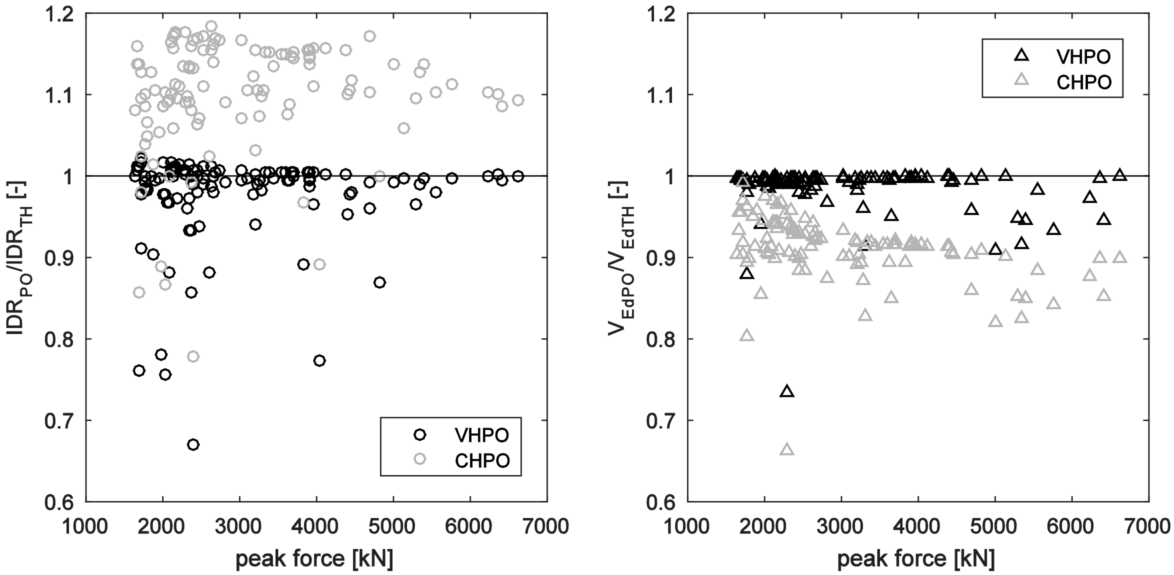


Fig. 5 - Time-history vs pushover analyses for two different tsunami wave traces: (a) and (c) force-displacement envelope; (b) and (d) maximum interstorey drift demand

Comparison of the three considered analysis methodologies can be performed in terms of normalised quantities (Fig. 6). The demand is assessed in terms of both base shear in column 1011 and maximum IDR at the ground storey, and the structural response predicted by the pushover methods is normalised with respect to that from the TH analysis. Figure 15 shows that VHPO provides a good estimate of both the shear and IDR for a wide range of tsunami time-histories. In a few cases, VHPO may induce an underestimation of IDR due to the above-mentioned double-peak in tsunami force time-history, i.e. up to 50% underestimation for low tsunami force applied in the first cycle/peak. It is noted that as the applied tsunami force of the first cycle/peak increases, the discrepancy between VHPO and TH diminishes since the structure is already subjected to large nonlinearity by the time the second cycle is applied. CHPO is observed to result in a worse prediction of the structure response with respect to TH as compared to VHPO. It is seen to overestimate IDR and underestimate shear in column 1011 by 5%-20% in both cases. A significant overestimation of IDR is exhibited close to collapse, which can be explained by the lower peak force and the pushover curve shape of CHPOs (Fig. 3). In both cases of

VHPO and CHPO, the double-peak traces result in the largest discrepancies in IDR prediction, but do not affect the dispersion of results for base shear, as would be expected.



(a) (b)

Fig. 6 - Estimation of the bias induced by nonlinear static analyses for (a) IDR and (b) shear demand, for the triangular load pattern

4. Conclusions

Current guidelines for the design and assessment of buildings under tsunami actions do not explicitly state how best to apply the tsunami loads to the building in structural analysis nor which analysis methods to use in order to assess the structural response to the tsunami loads. Despite the recognised limitations of this study (i.e. a single case study structure that is assumed impermeable; buoyancy forces and debris impact are neglected; and only triangular and trapezoidal net force distributions are assumed), this paper provides some initial guidance on both these points.

The paper presents a comparison of different nonlinear static analyses versus dynamic analyses in assessing tsunami impact on buildings. In particular, three different analysis methodologies of constant-height pushover (CHPO), variable-height pushover (VHPO), and time-history (TH) analyses are compared in terms of their abilities to predict structural response. A reinforced concrete frame tsunami evacuation building is selected as a case study for the comparative study and is subjected to the simulated 2011 Tohoku tsunami inundation flows. A tsunami inundation simulation is employed to define a set of tsunami inundation time-histories in terms of inundation depth and flow velocity at different sites in the Tohoku region of Japan. Tsunami force is evaluated according to a recent formulation, which is modified in this study in order to be applicable to a generic tsunami inundation trace. Two different load patterns, i.e. triangular and trapezoidal, are adopted to distribute the tsunami force along the height of the structure.

The two pushover analysis methodologies, i.e. CHPO and VHPO, are compared to TH analysis in terms of their abilities to predict structural response for an extensive set of simulated tsunami inundation time-histories. It is found that the results of VHPO provide a good prediction of the engineering demand parameters obtained from the TH analysis under a wide range of tsunami time-histories. CHPO gives a worse prediction of the demand; it overestimates interstorey drift ratio and underestimates column shear by about 5-20%. On the basis of these results, it can be concluded that PO methods are a good proxy for TH. In particular, it is recommended that VHPO be used in future fragility analysis of buildings subjected to tsunami. It should be highlighted that pushover methods are found to be inadequate in cases where the tsunami inundation force time-history is characterised by a double-peak, which subjects the structure to a two-cycle load.

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