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Vulnerability and resilience under effects of tsunamis: case of industrial plants

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Abstract

The damages caused by natural or technological hazards to physical systems may generate disastrous situations. However, the damaged systems can adapt, recover and be restored or strengthened in given acceptable recovery period for resilient systems. The metrics to evaluate objectively the resilience are still to be developed for several systems such as industrial plants, for instance. In fact, the resilience is intimately depending on both expected damages level and adaptation measures. The mechanical vulnerability is therefore an influent governing parameter. The present paper focuses on the case of industrial tanks and their mechanical vulnerability under tsunamis’ effect. The resilience of coastal industrial plants is implicitly investigated by running sensitivity analysis:

- Since tsunamis may cause structural failure of the tanks. Several modes of damages are considered, i.e. uplift by buoyancy, rigid overturning, rupture of anchorages or rigid sliding effect, and excessive stress by bending or buckling.
- For a wide range of tanks dimensions and filling ratios, the vulnerability and fragility curves are developed and discussed.

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Keywords: Tsunamis; Resilience; Vulnerability; Fragility; Hazard; Risk; Industrial plants; Metal tanks

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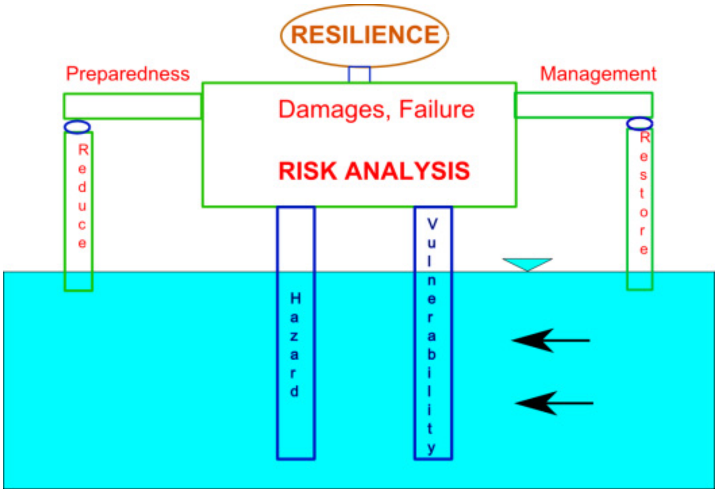
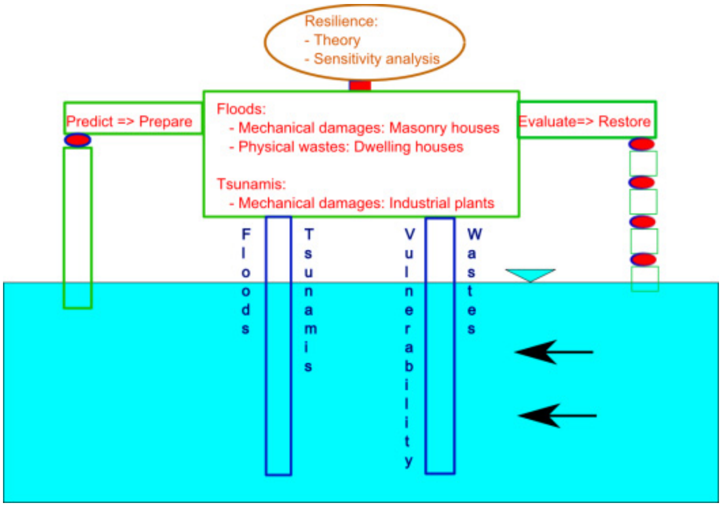
1. Introduction

The concept of resilience is well adapted to address the case of industrial plants and their vulnerability under the effects of natural hazards such as tsunamis, or industrial hazards such as explosions or fires. It investigates the capacity of the physical system and its related socio-economic aspects to stand the disturbances and damages, to adapt, recover and return into accepted conditions within a given recovery period, [1-16]. The resilience analysis of industrial plants still requires the development of rigorous and objective metrics [6], i.e:

- Identification and evaluation of given utility functions,
- Analysis and assessment of these functions losses, such as mechanical damages, under the effect of expected hazards(Fig.1),
- Definition of these functions threshold values, recovery periods for post-disaster stage, below which the system is considered as unable to become resilient.



(a)- *General layout*



(b)- *Applications and case studies*

Fig. 1. Layout for integrated framework: Hazard – Vulnerability – Risk – Resilience[6].

Obviously, the resilience depends intimately on the damage level caused by the potential hazards. For excessive values of the damage, the system will be unable to recover. It is therefore of great importance to be able to evaluate accurately the values of the expected or observed damages and to be able to develop objective and measurable indicators for the system's resilience, [6]:

$$F_R\left(t\right)\Big|_{T_{\mathrm{ref}}} = \iiint_{\mathrm{V}}\left[F(t).\left(1-D\right)\right].\left[(1+\Phi_r(t)\chi_r(t))\right].\mathrm{d}v \tag{1}$$

where: $F_R(.)$= Resilience function of the system during the recovery period or reference period T_{ref}; V= volume of the system; T_{ref}= recovery or reference period; t= instant ranging between the hazard occurrence and T_{ref}; $D(.)$= damage value or vulnerability ranging within [0..1]; $\Phi_r(.)$= recovery and evolution function, and $\chi_r(.t)$= resilience capability and availability function which depends on availability of resources (internal or external) and the capacity to react adequately, such as past experience, knowledge and preparedness.

Relevant resilience analysis requires that the vulnerability and fragility functions are accurately modeled. The present paper focuses on several parts of the integrated resilience framework for different mechanical systems:

- Mechanical vulnerability of industrial plants under the effect of tsunamis,
- Sensitivity analysis of the resilience indicator, i.e. utility functions depending on the intensity of damage and vulnerability, their threshold values and recovery time.

2. Vulnerability modeling

Under the hydrodynamic effects of the tsunamis, the structural vulnerability is investigated against several mechanical phenomena, (Fig.2):

- Tanks' uplift due to buoyancy,
- Debris impacts, perforation or collapse of tanks or sections of tank with the ensuing escape of stored products (oil, other liquids and gases),
- Excessive bending or shear, as well as rigid sliding and overturning,
- Circumferential as well as longitudinal buckling,
- Rupture of the pipes connected to the tanks and the metal roofs.

The vulnerability of the tanks is investigated for given levels of the tsunami's effects, i.e. its height and velocity, against the height of the liquid stored in the tanks, in order to consider various exploitation conditions. However, due to unknown conditions about the contact of the tank with its concrete support on the ground, this contact is described by a friction coefficient assumed to have a constant value all over the concrete support. This tank-fullness ratio is considered as a random variable following a theoretical Gamma distribution, [6]. The tank may fail when it cannot resist any of uplift effect, overturning moment, sliding effect as well as circumferential buckling effects. The failure event, E_f, is therefore described as being a serial combination of probabilistic elementary failures, [6]:

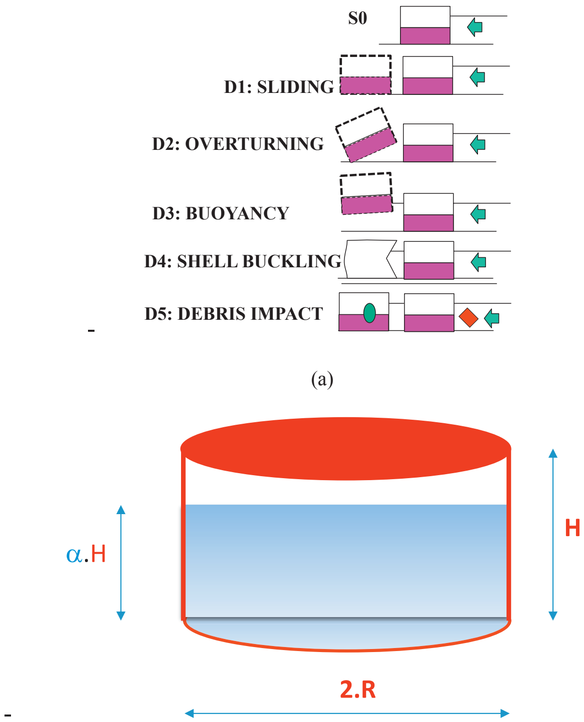
$$E_f = \bigcup_{i=1}^{N_e} E_{f,i} \text{ and } P_f = P\left\lfloor E_f \right\rfloor \tag{2}$$

where: E_f= failure event of the system; P_f= failure probability or vulnerability; $E_{f,i}$= i-th failure event among the total number N_e of failure events: for instance i=1 for Buoyancy, i=2 for perforation by debris impacts.

3. Fragility curves and failure risks

The failure risk of the metal tanks is defined as, [6-9]:

$$P_f = (R - S \leq 0) \tag{3}$$



(a)

(b)- Tanks: 5 sizes {T_1: H=8m, R=5.57m}; { T_2: H=10m, R=14m}; { T_3: H=19m, R=10m}; { T_4: H=30m, R=20m}; { T_4: H=30m, R=40m}

Fig. 2. Cylindrical metal tanks for storing oil in industrial plants: (a)- Failure modes of tanks; (b)- Various dimensions[6].

$$p_{\text{hydraulic}} = H_w + \frac{V_w^2}{2.g} \qquad (4)$$

where : R= structural capacity of the tank against any of the elementary mechanical events, i.e. uplift effect, overturning moment, sliding effect as well as circumferential buckling effects); S= mechanical effect of the tsunami, i.e. the effect of the hydraulic pressure $p_{\text{hydraulic}}$; $p_{\text{hydraulic}}$= hydraulic pressure resulting from the height (H_w) and the velocity (V_w) of flow, [6-7].

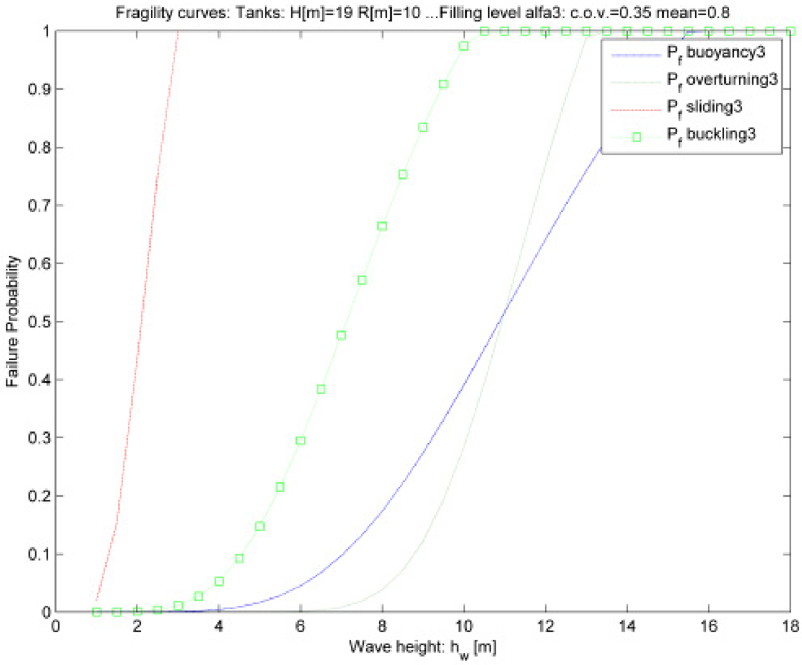
Monte Carlo simulations are used to calculate the risk of failure, [6-9]. The fragility curves express the probability of failure vs. *vs.* tsunami height (H_w). The risk analysis of the entire industrial plant, erected in a zone prone to tsunamis, relies on the use of these fragility curves specific to each type of tank, (Fig. 3).

4. Conclusions

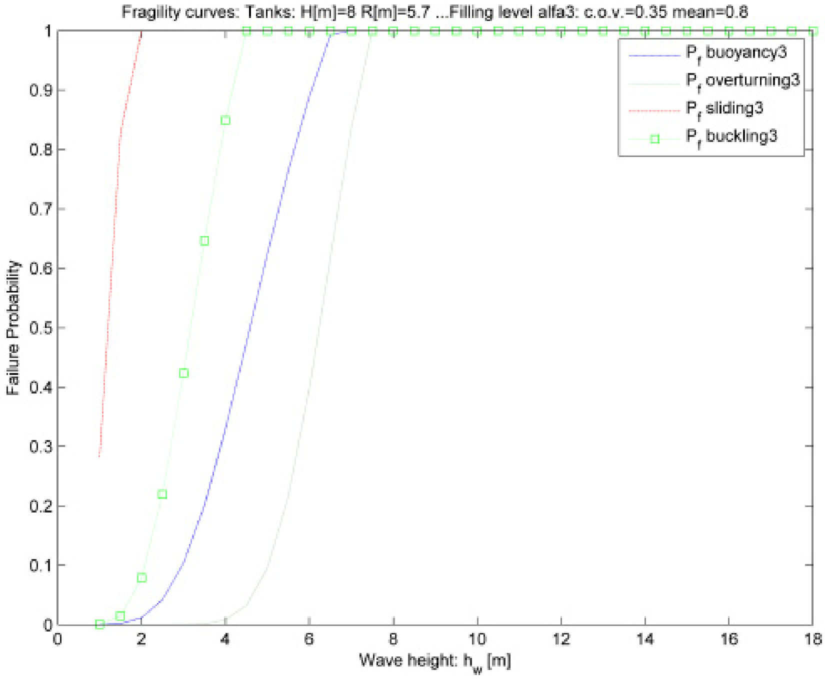
The concept of resilience is considered and discussed in order to address the case of industrial plants and their physical vulnerability under the effects of tsunamis hazards. Coastal industrial plants containing metal tanks and their fragility curves are investigated.

Simplified model valid at the shoreline (at normal sea level) and inland inasmuch as the terrain is flat have already been issued and the expected height and velocity of the tsunami flow are considered as known, [7].

The tsunami may cause mechanical failure of tanks by rigid sliding, buoyancy uplift, buckling or rigid overturning. New fragility curves vs. tsunami height are developed for typical tanks ranging from 8 m to 30 m high and from 10 to 80 m in diameter, used for oil storage. Two kinds of tanks are reported in the present paper.



(a) Multi failure modes= large size tanks



(b)Multi failure modes= small size tanks[6]

Fig 3. Cylindrical metal tanks for storing oil in industrial plants.

The results show that sliding has more severe effects than buckling, buoyancy or overturning in the case of small tanks, even if they are not empty. Lateral protective barrier should be considered even for large tanks since their resistance to sliding is also very weak. Otherwise, these tanks could slide and the pipes connected to them could break even if the tsunami is less than 3 meters high.

If adequate protections are considered against sliding, they can withstand tsunamis of almost 10 m before buckling and 15 m before they are damaged by buoyancy or overturning effects.

This sensitivity analysis is helpful for risk managers and their preparedness either to face potential hazards such as tsunamis or to design protective systems such as dikes, early warning and alert devices.

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