GEOMATICS, NATURAL HAZARDS AND RISK, 2016
VOL. 7, NO. S1, 5–17
http://dx.doi.org/10.1080/19475705.2016.1181458

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Natural hazards, vulnerability and structural resilience: tsunamis and industrial tanks

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ABSTRACT

The paper presents an integrated framework which deals with natural hazards (tsunamis), physical vulnerability modelling, risk of failure for industrial structures (metal structures) and structural resilience provided by plastic adaptation. Simplified models are proposed to describe the run-up and wave height attenuation in case of tsunamis. The results are calibrated in the case of important tsunamis having taken place in Asian region. The mechanical vulnerability of cylindrical metal tanks erected near the shoreline is also investigated. The fragility curves are then developed in order to describe the multimodal failure: overturning, rupture of anchorages and sliding, buoyancy, excessive bending effects or buckling. Corresponding fragility curves are developed under various conditions: height of tsunami waves, filling ratios and service conditions of the tanks, friction tank/ground as well as dimensions effects. Probabilistic description of the natural hazard and the fragility curves are presented. Sensitivity analysis is also performed in order to investigate the effect of various governing parameters. Furthermore, resilience concepts and metrics are proposed. Theoretical description of the damages and post-disaster recovery functions are discussed: plastic adaptation as well as elastic and plastic attractors.

ARTICLE HISTORY
Received 20 October 2015
Accepted 12 April 2016

KEYWORDS
Hazards; Tsunamis; resilience; structures; industrial tanks; fragility curves; vulnerability

1. Introduction

Resilience is becoming a powerful and integrated concept able to deal with the case of individual structures as well as sets of structures at large scales such as industrial plants, urban or regional infrastructures. It is actually well adapted for quantitative description of the system post-disaster behaviour or capacity. This capacity may concern mechanical and physical response as well as socio-economic aspects.

However, objective resilience measurement requires adequate metrics and effective description of the system recovery functions at post-disaster stages as well as the assessment or prediction of the damage that may be caused by the potential hazards. For instance, during *2011 Tohuku earthquake* and tsunami event, several industrial plants have suffered irreversible damages and have generated important socio-economic consequences, with domino effects since first damages propagated and caused subsequent failures and disturbance in the interrelated dependent systems. Obviously, the structural residual capacity and the socio-economic recovery functions depend on the losses extent,

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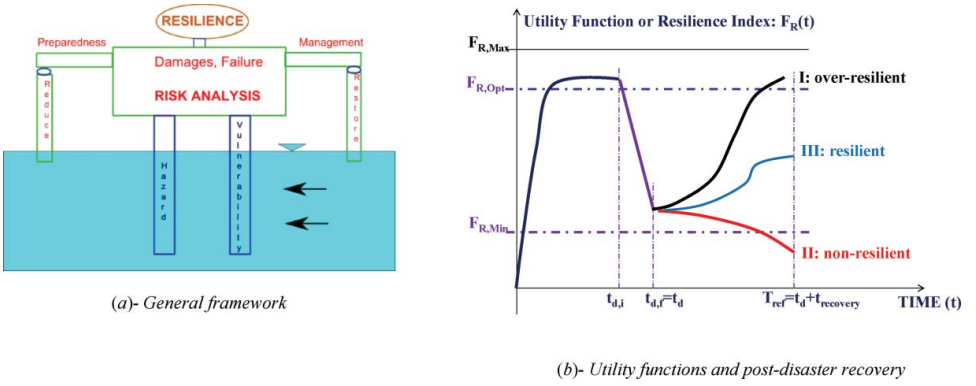


Figure 1. Integrated framework: hazard – vulnerability – risk – resilience (Mebarki et al. 2014a, 2014b; Mebarki and Barroca 2015). (*a*) General framework and (*b*) utility functions and post-disaster recovery.

i.e. damages, the available resources and the post-disaster management. It is then of crucial importance to develop adequate functions and metrics able to define, see figure 1:

- The utility functions of a system at each instant time t, i.e. $F_R(.)$ which expresses the mechanical capacity or socio-economic aspects and its threshold value $F_{R,\min}$ for 'survival' and possible upper bound value $F_{R,\max}$,
- the potential hazards (natural or industrial),
- the vulnerability and fragility functions of the system, for each intensity of the hazard,
- the conditional damages and losses caused to the utility functions, conditional to each hazard intensity,
- the system 'survival' after the disaster is triggered (at $t_{d,i}$ and lasting until $t_{d,f}$) and
- the recovery functions according to the available resources (intern resources due to adaptation between the system components, or extern resources by flow exchanges) and the adequate management or by change of use (and subsequent utility functions) and threshold value for resilient systems ($F_{R,\text{opt}}$), during a reference period for recovery (T_{ref}).

For illustrative purposes, cylindrical metal tanks, erected in a petrochemical plant at a coastal zone, are studied. Simplified probabilistic tsunamis models are developed and calibrated according to the real wave heights and collected run-ups values. The structural behaviour of the tanks and their fragility functions are also elaborated. The potential and conditional damages that may be caused to the tanks are also described by probabilistic models. Sensitivity analysis and discussion about metrics for resilience are also proposed.

2. Resilience and metrics

The resilience is widely used for dynamic systems in order to describe their ability to absorb, stand and recover from catastrophic events. However, the most common resilience analyses deal with descriptive and qualitative analysis. It is then still challenging to define consensual metrics for quantitative resilience analysis (Hollnagel et al. 2008; Johnston et al. 2008; Hollnagel et al. 2011; Stewart & Yuen 2011; Barker et al. 2012; Dinh et al. 2012; Miller-Hooks et al. 2012; Shirali et al. 2012; Francis & Bekera 2014; Manyena 2014; Matthews et al. 2014; Pant et al. 2014; Roege et al. 2014; Shafieezadeh & Burden 2014; Aldunce et al. 2015; Angeon & Bates 2015; Bond et al. 2015; Cardoso et al. 2015; Chopra & Khanna 2015; Dijkstra & Viebahn 2015; Kelman et al. 2015; Khalili et al. 2015; Labaka et al. 2015; Lindbom et al. 2015; Lundberg & Johansson 2015; Mugume et al. 2015; Oken et al. 2015; Ouyang & Wang 2015; Righi et al. 2015; Sahebjamnia et al. 2015).

Quantitative and relevant resilience metrics obtained as improvements of metrics already issued can be expressed as (Mebarki et al. 2014a, 2014b; Mebarki & Barroca 2015):

$$F_R(t) = F_R(t \mid_{V,\partial V,T_{\mathrm{REF}}}) = \left[F_R(t_{d,i}).\left(1 - [H(t - t_d \geq 0).D_{\mathrm{Fr}}(t_d)]\right)\right].\left[(1 + \Phi_a(t - t_d).\chi_{m,c}.\chi_{m,r}\right] \quad (1)$$

$$\Phi_a(t - t_d) : \begin{cases} \Phi_a(t - t_d) > 0 : & \text{if the system recovers (strengthening or hardening)} \\ \Phi_a(t - t_d) = 0 : & \text{if the system stays at stationary state or plastic perfect} \\ \Phi_a(t - t_d) < 0 : & \text{if the system state decreases (worsening or softening)} \end{cases} \quad (2)$$

$$\chi_{m,r} = \begin{cases} \chi^{I}_{m,r} : & \text{for parallel events, i.e. need for both external and internal resources for recovery} \\ \chi^{II}_{m,r} : & \text{for serial events, i.e. need for either external or internal resources for recovery} \end{cases} \quad (3)$$

$$\chi^{I}_{m,r} = \chi^{\mathrm{int}}_{m,r}.\chi^{ext}_{m,r} : \begin{cases} 1: & \text{if external as well as internal resources are potentially available} \\ 0: & \text{if neither external nor internal resources are potentially available} \end{cases} \quad (4)$$

$$\chi^{\mathrm{II}}_{m,r} = 1 - (1 - \chi^{\mathrm{int}}_{m,r}).(1 - \chi^{ext}_{m,r}) : \begin{cases} 1: & \text{if either external or internal resources are available} \\ 0: & \text{if neither external nor internal resources are available} \end{cases} \quad (5)$$

$$H(t - t_d \geq 0) = \begin{cases} 1 : & \text{if } (t - t_d) \geq 0 \\ 0 : & \text{else} \end{cases} \quad (6)$$

where $F_R(.)$ = resilience index or utility function value at instant t; $t_{d,i}$ = instant at which the hazard is triggered, such as the tsunamis' flows arrival time; ($t_d = t_{d,f}$) = end of the hazard application such as tsunamis sequence end (for short duration events such as earthquake or explosion: $t_d = t_{d,f} = t_{d,i}$); $D_{\mathrm{Fr}}(.)$ = damage value or physical vulnerability ranging within [0..1] which corresponds to the resilience drop caused by the disaster; $H(.)$ = Heaviside function; V = entire system volume (local or global scale); jV = its frontier; T_{ref} = reference or conventional period for expected recovery; $\Phi_a(t)$ = adaptation and recovery evolution function under given hypothetic availability of resources and adequacy of management; χ_m = probability measure of readiness and adequate management for 'resilience capability and resources availability' function which depends on $\chi_{m,r}$ = probability of having available resources within the system volume or/and as flow exchanges at its frontiers and $\chi_{m,c}$ = probability of adequate management by 'resilience building capacity' which expresses the actual capacity to react adequately. This later depends mainly on past experience, education, knowledge and readiness to react, 'faith' in possible solution, as well.

According to the resilience index value along the reference period, the system will be then considered as:

- non-resilient if $\{(F_R) < (F_{R,\min})\}$,
- resilient if $\{(F_R) \in [F_{R,\min}; F_{R,\mathrm{opt}}]\}$,
- over-resilient if $\{(F_R) > F_{R,\mathrm{opt}}\}$.

3. Case of metal tanks and industrial plants: resilience, basins and attractors

For illustrative purposes, the case of metal tanks erected in a petrochemical plant under the lateral pressure of tsunamis is investigated. Though they have usually tubular cross sections, for the sake of simplicity in the present analytical developments, the case of rectangular cross sections is developed whereas the equivalent metal beams are supposed to have either one or two fixed supports, see

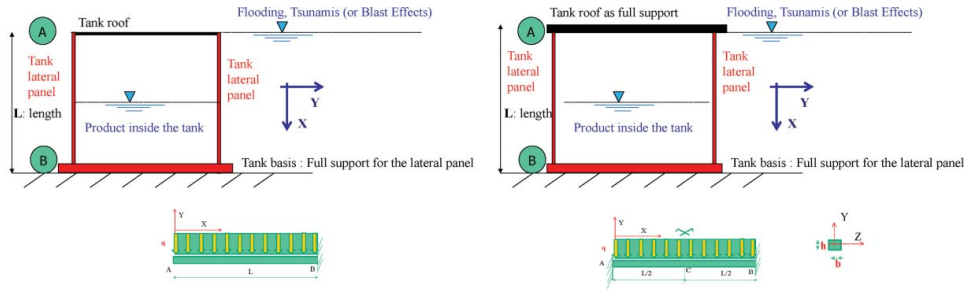


Figure 2. Metallic tanks and equivalent structural beam models under uniform lateral pressure. (*a*) One fixed support tank and structural model and (*b*) two fixed supports, cross-section and structural model.

figure 2. A conventional quantitative structural resilience $F_R(.)$ can be expressed as:

$$F_R(t) = \frac{q_R(t)}{q_{\text{el}}} \tag{7}$$

with $q_R(.)$ = the residual bearing capacity, i.e. the maximal tsunami pressure that can still be resisted by the structure; q_{el} = the 'elastic pressure' for which the extreme fibre of the structure reaches the yielding stress f_y.

The conventional resilience is so that the structure is expected to absorb at any time a load able to generate a maximum stress strictly equal to the yield stress f_y of the constitutive tank metal. A resilient system will recover, by plastic adaptation, so that its residual capacity satisfies:

$$F_R(t)\big|_{T_{\text{Ref}}} \geq 1 \tag{8}$$

It is also necessary to define a corresponding conventional potential for resilience, such as:

$$\Theta_R(t)\big|_{T_{\text{ref}}} = 1 - F_R(t)\,|_{T_{\text{ref}}} \tag{9}$$

Therefore, several particular values of this potential resilience can be defined:

- *Initial state:* before any damage affects the structure, the potential for resilience is:

$$\Theta_R(t < t_d)\big|_{T_{\text{ref}}} = 1 \tag{10}$$

- *Elastic attractor:* when the bearing capacity is equal to the elastic value q_{el}, the potential for resilience becomes:

$$\Theta_R(t = t_{\text{el}})\big|_{T_{\text{ref}}} = 0 \tag{11}$$

This value defines, therefore, the reference line (elastic attractor) above which the structure is non-resilient.

- *Resilience drops due to damages at critical sections:* when the critical sections suffer damages (edge or mid-span damages), then the potential increases and the system needs to return to negative values of this potential in order to become resilient. Due to plastic resources available at the damaged critical section, the potential for resilience moves towards the plastic attractor

defined by:

$$\Theta_R(t=t_{\mathrm{pl}})\big|_{T_{\mathrm{ref}}}=\begin{cases}1-F_R^{\mathrm{rec}}=1-(1-D_h^{\mathrm{edge}})^2.G_{\mathrm{area}}: \text{ case of structure with one full support}\\ 1-F_R^{\mathrm{rec}}=\left(1+(1-D_h^{\mathrm{edge}})^2\right) \quad : \text{ case of structure with two full supports}\end{cases} \tag{12}$$

$$\begin{aligned}&D_h=D_h^{\mathrm{edge}}=\text{damage at the edge (drop of residual resisting height } h)\\ &G_{\mathrm{area}}=\frac{W_{\mathrm{pl}}}{W_{\mathrm{el}}} \qquad \text{where } G_{\mathrm{area}}=\frac{(b.h^2/4)}{b.h^2/6}=1.5 \text{ for rectangular cross section}\end{aligned} \tag{13}$$

- *Final basin attractor due to complete use of available resources for recovery and interaction between critical sections:* when the whole resources (plastic behaviour) are used for the capacity recovery, the structure reaches the final resilience basin. For the case of one full support, the final resilience basin is at the same resilience potential value than the plastic attractor. For the two full supports case, this final basin depends on the resources available at the mid-span (full section yielding capacity). The post-recovery basin becomes then:

$$\Theta_R(t=t_{\mathrm{rec}})\big|_{T_{\mathrm{ref}}}=\begin{cases}1-F_R^{\mathrm{rec}}=1-(1-D_h^{\mathrm{edge}})^2.G_{\mathrm{area}}: \text{ case of one full support}\\ 1-F_R^{\mathrm{rec}}=\dfrac{2.G_{\mathrm{area}}}{3}.\left((1-D_h^{\mathrm{edge}})^2+(1-D_h^{\mathrm{span}})^2\right) : \text{ case of two full supports}\end{cases} \tag{14}$$

$$\begin{aligned}D_h^{\mathrm{span}}=&\text{damage at the mid-span cross section of the metal beam}\\ &\text{(drop of residual resisting height } h)\end{aligned} \tag{15}$$

Hypothesis - In order to express the time-dependent recovery process and simulate the load evolution vs. time, the load q is supposed to vary uniformly with the time, i.e. it is supposed to increase or decrease with the same velocity, i.e.:

$$\dot{q}=\left|\frac{dq}{dt}\right|=\text{constant} \tag{16}$$

Various damage conditions are considered. The resulting resilience as well as the corresponding potential for resilience is reported:

- For a metal tank with one full support, see figure 3: the structure is resilient as long as the bottom section damage satisfies:

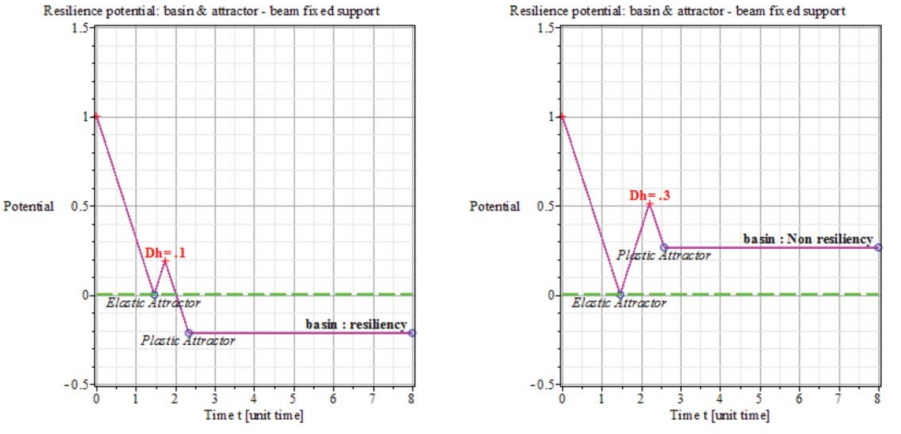
$$D_h^{\mathrm{edge}}\leq\left\{1-\sqrt{\frac{2}{3}}=0.184\right\}$$

, see equations (12−13)

- For a metal tank with two full supports at the bottom and at its top (rigid roof), see figure 4: the structure is resilient as long as the damages caused at the bottom and the top sections satisfy the condition:

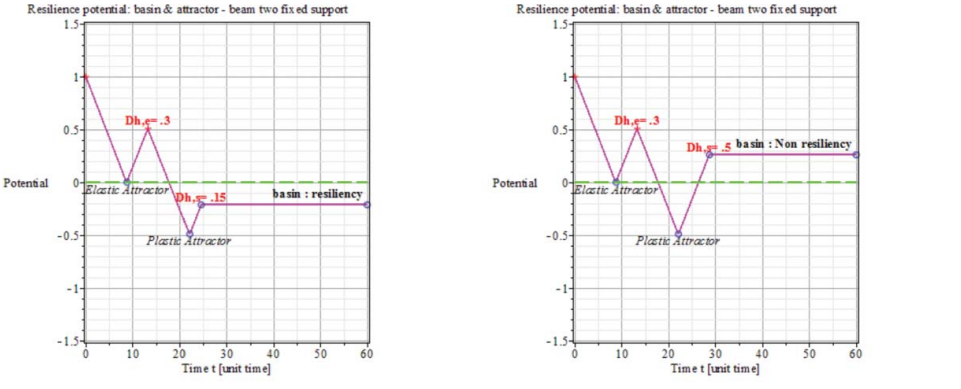
$$(1-D_h^{\mathrm{edge}})^2+(1-D_h^{\mathrm{span}})^2\geq 1$$

, see equations (12−13).



(*a*)- Resilient tank: $\mathrm{D_h} = \mathrm{D_h^{edge}} = 0.1$ (*b*)- Non-resilient tank: $\mathrm{D_h} = \mathrm{D_h^{edge}} = 0.3$

Figure 3. Beam on one fixed support and potential resiliency: basins and attractors. (*a*) Resilient tank: $D_h = D_h^{\text{edge}} = 0.1$ and (*b*) non-resilient tank: $D_h = D_h^{\text{edge}} = 0.3$.



(*a*)- Resilient tank: $\mathrm{D_h^{edge}} = 0.3; \mathrm{D_h^{span}} = 0.15$ (*b*)- Non-resilient tank: $\mathrm{D_h^{edge}} = 0.3; \mathrm{D_h^{span}} = 0.5$

Figure 4. Beam on two fixed supports and potential resiliency: basins and attractors. (*a*) Resilient tank: $D_h^{\text{edge}} = 0.3$; $D_h^{\text{span}} = 0.15$ and (*b*) non-resilient tank: $D_h^{\text{edge}} = 0.3$; $D_h^{\text{span}} = 0.5$.

4. Hazard modelling: case of tsunami

Numerous investigations have focused on tsunamis modelling, simulations and observations analysis (Abe 1993; Demetracopoulos et al. 1994; Abe 1995; Haugen et al. 2005; Wijetunge 2006; Burwell et al. 2007; Helal & Mehanna 2008; Constantin 2009; Heidarzadeh et al. 2009; Liu et al. 2009; Zhang et al. 2009; Madsen 2010; Lovholt et al. 2012; Cheung et al. 2011; Flouri et al. 2013; Goto et al. 2011; Nandasena et al. 2011; Pophet et al. 2011; Zhao et al. 2011). A probabilistic simplified model, adapted from attenuation models for earthquakes, is developed and presented for evaluation of the peak water heights (H) and run-ups (H_R) during tsunamis (Mebarki 2009; Mebarki et al. 2014a, 2014b; Mebarki & Barroca 2015). A Gamma distribution is adopted to describe the uncertainties

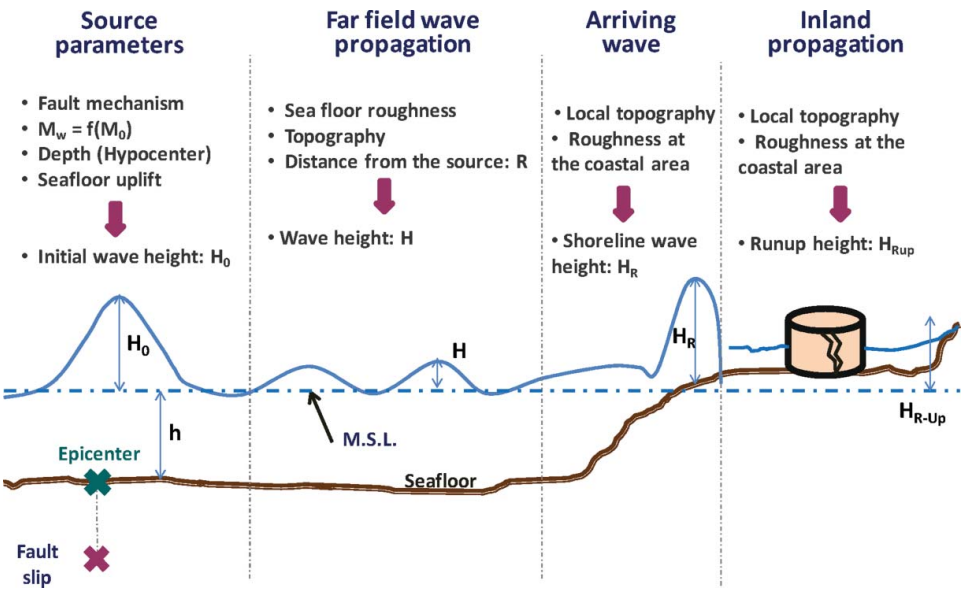


Figure 5. Tsunami path from the epicentral zone towards the shore and inlands.

affecting the model and the parameters, see figure 5:

$$\frac{H}{H_0} = \frac{e^{-\beta.D_h}}{1 + D_h.e^{-(M_w - M_0)}} \tag{17}$$

$$\log(H_0) = 0.5M_w - 3.3 + C(Abe\ 1993) \tag{18}$$

$$V = \sqrt{g(h+H)} \tag{19}$$

where H (m) = peak water height; h (m) = water depth; D_h (km) = hypocentral distance; M_w = earthquake moment magnitude; H_0 (in m) = reference uplift at the epicentral zone, M_0 = threshold magnitude and β are fitting parameters; C = constant value considered as fitting parameter depending on the kind of subduction zone (Abe 1993, 1995); and V: velocity of the tsunamis.

Near the shoreline, the seabed is supposed to be represented by a straight line from an interface distance until it reaches the shoreline (SL), see figure 6. The peak water height at the shoreline is

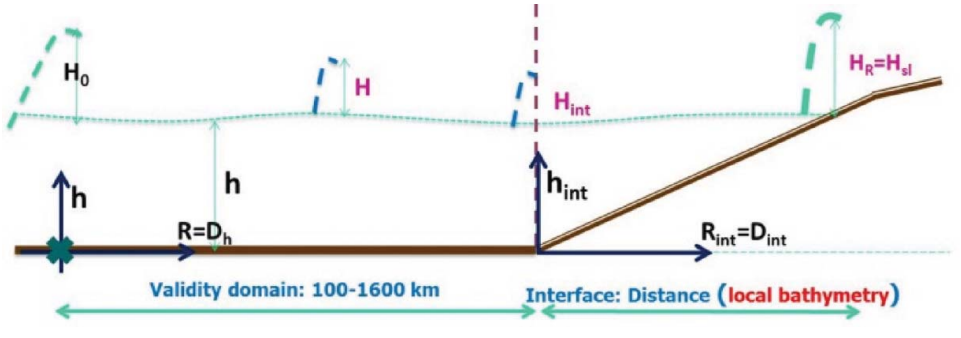


Figure 6. Run-up and slopes between interface zones and shorelines.

obtained by energy conservation, when no attenuation is considered, i.e.:

$$H_{sl}^2 . \sqrt{H_{sl}} = H_{int}^2 . \sqrt{(h_{int} + H_{int})} \tag{20}$$

Due to the energy dissipation (attenuation), the final peak water height at the shoreline becomes then:

$$H_{sl} = (H_{int}^2 . \sqrt{(h_{int} + H_{int})})^{2/3} . \frac{e^{-\beta . D_{int}}}{1 + D_{int} . e^{-(M_w - M_0)}} \tag{21}$$

where H_{sl} (in m) = peak water height at the shoreline, H_{int} (in m) = peak water height at the interface zone, h_{int} (in m) = depth of the sea at the interface zone, D_{int} (in km) = horizontal projection of the distance from the interface zone towards the shoreline.

To calibrate the model, the peak water heights observed during Akita Oki earthquake (Japan on 25 May 1983 with moment magnitude M_w = 7.9 (Abe 1995)) are simulated according to the bathymetry collected for the zones under study (GEBCO 2012). The model provides theoretical values that are in good accordance with the observed heights (H_{obs}), see figure 7. Furthermore, the theoretical confidence interval ($H_{5\%}$ up to $H_{95\%}$) contains 95% of the experimental values, i.e. more than the acceptable ratio of 90%, when the gamma distribution and a coefficient of variation C_v = 45% are adopted for the error model.

5. Mechanical fragility, vulnerability and damages due to tsunamis

The tsunamis hydrodynamic effects on the tanks may cause various mechanical failures and damages, see figure 8 (Godoy 2007; Goto 2008; Koshimura 2009; Leone et al. 2011; Lukkunaprasit 2009; Mebarki 2009; Sakakiyama & Matsuura 2009; Nistor et al. 2010; Norio et al. 2011; Chen 2012; Naito et al. 2013; Mebarki et al. 2014a, 2014b; Mebarki & Barroca 2015):

- Uplift phenomena due to buoyancy,
- debris impacts, perforation or collapse of tanks or rupture of the pipes connected to the tanks and the metal roofs, with subsequent leakages of stored products (oil, other liquids and gases),
- excessive bending or shear as well as circumferential and longitudinal buckling of the metallic shells,
- rigid sliding by anchors failures and overturning,
- various exploitation conditions, dimensions and ground support conditions are considered in order to investigate the tanks vulnerability under the tsunami effects (Mebarki 2009; Mebarki et al. 2014a, 2014b, Mebarki & Barroca 2015),
- the quality of the contact of the tanks on the supporting concrete slabs is described by a friction coefficient assumed to have a constant value all over the concrete support and
- depending on the exploitation conditions and tsunami occurrence, the tank may be empty, full or partially filled. The level of the stored product in the tank is assumed to follow a random Gamma distribution (extreme events).

The tank failure corresponds to the first occurrence of any limit state among the potential list of mechanical failures: uplift, overturning, sliding or buckling. The debris effects such as containers or boulders impacts for instance are not reported in the present study. The failure event, E_f, is therefore described as being a serial combination of independent probabilistic elementary failures:

$$E_f = \bigcup_{i=1}^{N_e} E_{f,i} \text{ and } P_f = P[E_f] \tag{22}$$

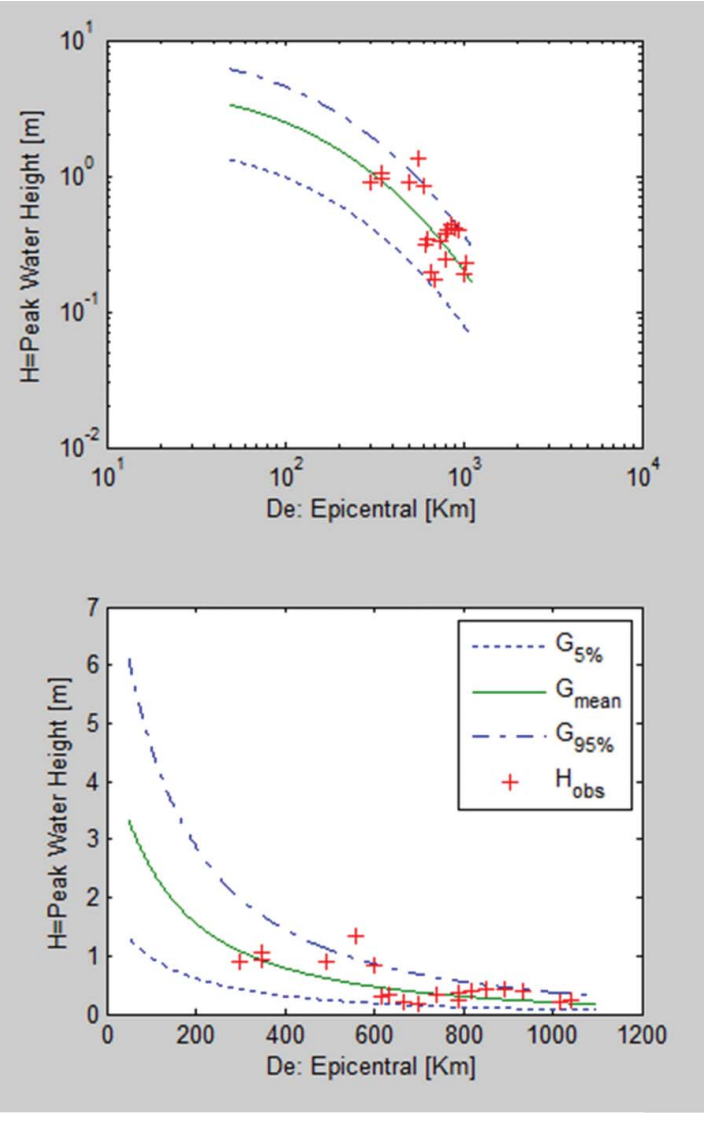


Figure 7. Tsunamis height. (a) Several failure modes and (b) tanks : forms and dimensions.
(Note: H_{obs} = observed value; G_{mean}, $G_{5\%}$, $G_{95\%}$ = predicted mean value, fractiles 5% and 95%, respectively).

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.

Monte Carlo simulations are used to calculate the risk of failure. The fragility curves express the probability of failure *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, see figure 9. The simulation results show that failure by sliding occurs prior to buckling, buoyancy or overturning in the case of small tanks (8 m height and 5.7m radius) even if they are not empty. It is also shown that the sliding failure which occurs as first limit state even for large tanks (30 m high and 40m radius). It is then recommended to erect lateral and circumferential protective barriers. Otherwise, these tanks could slide and the pipes connected to them could break even if the tsunami is less than 3 m high for small tanks and 6−8 m high for larger tanks. With adequate barriers and

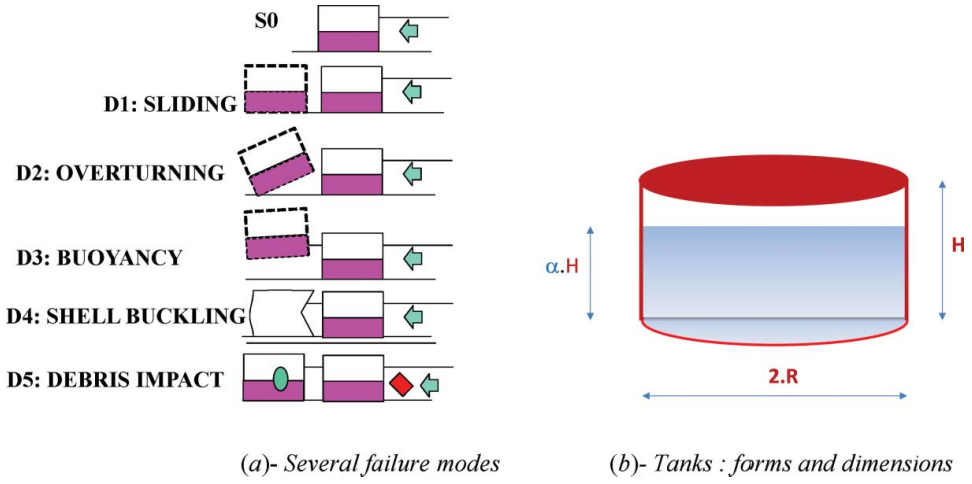


Figure 8. Cylindrical metal tanks for storing oil in industrial plants: (*a*) failure modes of tanks; (*b*) various dimensions: 5 sizes {T_1: H = 8 m, R = 5.57 m}; {T_2: H = 10 m, R = 14 m}; {T_3: H = 19 m, R = 10 m}; {T_4: H = 30 m, R = 20 m}; and{T_4: H = 30 m, R = 40 m}.

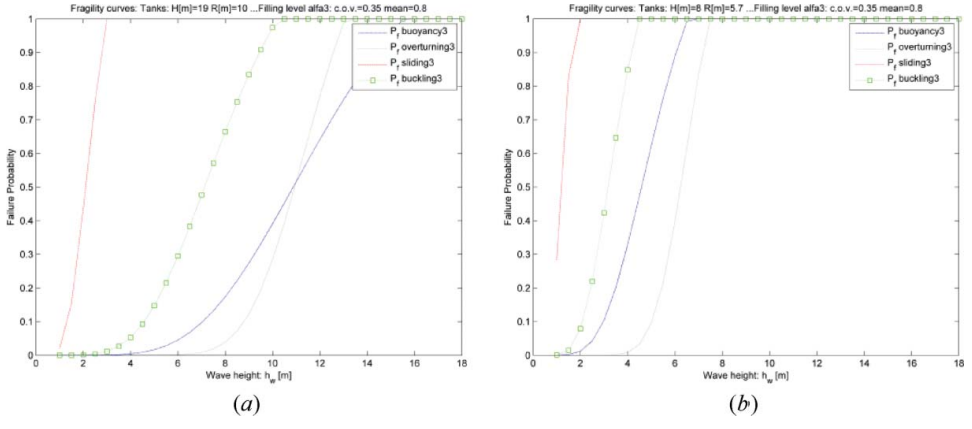


Figure 9. Cylindrical metal tanks for storing oil in industrial plants: (*a*) large size tanks and (*b*) small size tanks.

well-designed anchors against sliding, these tanks can withstand tsunamis of almost 10 m before buckling and 15 m before they are damaged by buoyancy or overturning effects.

6. Conclusions

Metrics for resilience are proposed in the case of coastal industrial plants and the tanks vulnerability analysis is investigated under tsunamis effects. The resilience depending on plastic adaptation is discussed in the case of metallic tanks with single full support (rigid basis) or double full supports (rigid basis and roof). The resilience indicators and attractors are investigating for various cases of cross-sections drops caused by physical damage due to first hazard occurrence, corrosion, debris impacts or prior excessive stresses by bending or shear for instance.

A unified methodology for reliability analysis is also developed. It proposes a new simplified probabilistic model able to predict the tsunami wave height as well as the run-up at the shoreline. Calibrated for real tsunamis, its theoretical predictions are in accordance with the in-situ tsunamis wave heights observed in Asian region at distances ranging from hundreds to thousands or kilometres from the seismic hypocentre (case of tsunamis triggered by earthquakes).

As the tsunamis may cause tanks mechanical failure by rigid sliding, buoyancy uplift, buckling or rigid overturning, theoretical fragility curves vs. tsunami height are established. They concern tanks with various dimensions: heights ranging from 8 to 30 m with diameters ranging from 10 to 80 m, used for oil storage.

The theoretical results show that sliding occurs prior to buckling, buoyancy or overturning in the case of small tanks, even if they are not empty. Therefore, lateral and circumferential protective barriers should be erected 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 m high. With adequate protections and better anchors resistance against sliding, the investigated tanks can withstand tsunamis of almost 10 m before buckling and 15 m before they are damaged by buoyancy or overturning effects.

The proposed framework is very helpful for coastal industrial plants, erected in regions prone to flooding by tsunamis for instance. Sensitivity analysis may help the risk managers for their preparedness in facing tsunamis and floods or to design adequate protective barriers such as dikes.

Acknowledgments

Several research projects have been helpful for collecting results and methodological developments: research projects with partial financial support by the Chinese-French program PHC-Cai Yuanpei ('*Havu-Risk: Chemical industrial plants & domino effect: hazards, vulnerability, risks & sustainability*' 32114TE, 2014-2016), Japanese-French ANR flash project (2011−2012) and the undergoing French collaborative Project '*IMFRA2.*'

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Chinese-French program PHC-Cai Yuanpei ('*Havu-Risk: Chemical industrial plants & domino effect: hazards, vulnerability, risks & sustainability*' 32114TE, 2014−2016); Japanese-French ANR flash project (2011−2012); the undergoing French collaborative Project '*IMFRA2.*'

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