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COMPARED EFFECTS OF EARTHQUAKES, TSUNAMI AND AIRCRAFT CRASHES ON BASE-ISOLATED MASSIVE STRUCTURES

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ABSTRACT

The purpose of this paper is to compare the respective effects of earthquake, tsunami and aircraft crash on typical base-isolated massive structures. Simple formulas are established for calculating the tsunami induced force as a function of the wave height and the response to this force. Similarly, formulas are established to calculate the response under aircraft crash, based on the mass and velocity of the aircraft. A key point is that base-isolation systems are tuned on such a low eignenfrequency (typically between half a hertz and one hertz) that the seismic input motion should be regarded as a displacement controlled load (the concept of equivalent static inertia load does not pertain), while the tsunami wave is a force-controlled load and the aircraft crash impact is a momentum-controlled load.

INTRODUCTION

Since the 70's France has been a pioneering country for the construction of nuclear installations on seismic isolation systems, starting with the Cruas-Meysse NPP (commercial operation in 1984) until the fusion prototype, ITER, under construction at Cadarache. An overview of seismically isolated French facilities was presented by Moussallam et al (2013) and Labbé (2013). A French standard on the subject was issued by AFCEN (2014). The French isolation technology is the multilayer neoprene (artificial rubber) bearing, for which a large experience feedback was already available in the 70's from bridges in operation. The same technology, supplemented by sliding plates, was used by French companies for the construction of the Koeberg NPP in South Africa (commercial operation also in 1984). The mechanics of multilayer rubber bearings has been analysed in detail by Kelly (2011).

Nowadays, the isolation technique is getting more and more interest around the world, not only for nuclear but also for other massive structures. For instance, the terminal buildings of the San Francisco airport (Zayas & Low 2000), the Kunming airport (Shu et al. 2008) and the Istanbul Sabiha Gökçen International Airport (Zekioglu et al, 2009) are seismically isolated. A major interest for airport buildings is that seismic isolation techniques significantly decrease their structural cost.

A paper on the effects of tsunami waves on seismically isolated buildings was recently published by Takayama (2013), dealing with more conventional structures. Of course the conclusion is that the capacity of seismically buildings to survive a tsunami depends on the height of the wave. However the trend is that seismically isolated conventional building can only survive very limited waves.

FEATURES OF SEISMICALLY ISOLATED MASSIVE STRUCTURES

Basically the concept of seismic isolation leads to the fact that, when considering their seismic response in horizontal direction, a seismically isolated building can be regarded as a rigid body installed on the isolation system. It means that the response, for instance in the X direction, is the one of a single degree of freedom system.

For the Cruas-Meysse NPP, which was the first seismically isolated nuclear installation In France, the eignenperiod of the considered SDOF was selected at 1 s. Afterwards the trend has been to increase this eigenperiod up to close to 2 s for ITER. Regarding airport terminal buildings, the one of Kunming is also based on a rubber bearing system, with a 0.75 s eigenperiod. The Istanbul and San-Francisco airport terminal buildings are based on friction pendulum systems, both designed with a 3 s isolated period. For the purpose of this paper the main point is that the isolated period of an isolated building is typically of 1 s or more (its eignenfrequency is around 1 Hz or smaller). For the purpose of numerical applications we select a 2 s eigenperiod (0.5 Hz eignenfrequency).

A large isolated period is efficient to reduce the acceleration transmitted to the superstructure and consequently to minimize the seismically induced forces. A benefit is that it results in lower construction costs. On the other hand, a detrimental consequence is that the differential displacement between the isolated structure and the "external world" increases. Optimal design results from a trade-off between advantages and drawbacks. Depending on the type of earthquake to be considered the expected displacement varies significantly. For instance, in the case of Cruas-Meysse in France, the design displacement is only 6 cm (displacement at 1 Hz and 5% damping for a design spectrum anchored at a 0.3 g PGA), while in the case of the San-Francisco airport, it is 50 cm.

Both friction pendulum and multilayer rubber bearing have in common that they provide isolation against the horizontal component of the input motion, but they transmit the vertical input without filtering effect. In the following, we are going to consider only the case of multilayer (natural or artificial) rubber bearings. According to AFCEN (2014) the main features of this type of bearings are as follows:

- The shear strain that leads to the de-lamination of the multilayer bearing pads is larger than 350%. For the purpose of design, the acceptable shear deformation under exceptional conditions such as earthquake, tsunami, or aircraft crash, is limited to 140%. In the following we adopt 140% as design value for numerical applications and, for the rationale we regard 350% as the actual ultimate capacity of the system.
- The vertical compressive stress on the bearing system, σ_n, should be around 7-8 MPa. For numerical applications, we select 7.5 MPa.
- The effective value of the rubber dynamic shear modulus, G, is reported to vary from 0.7 to 1.1 MPa on the considered French installations and up to 1.4 MPa for the Koeberg system (Moussallam et al. 2013). For numerical applications, we select G=1.2 MPa.
- The effective reduced damping, ξ_0, varies from 5% to 7.5%. We select ξ_0=5% for numerical applications,

Regarding the multilayer rubber technology, the outlines of the system design procedure are basically as follows:

- The mass of the building, M, is the input data. The total surface of the isolation system, S, is calculated as: $S=M\, g/ \sigma_n$, g being the gravity.
- A target isolated period, T_0, is selected. Consequently the isolation system stiffness K_0 is calculated as: $K_0= M\,(2\pi\, f_0)^2$., with $f_0=1/T_0$.
- The cumulated thickness of rubber layers, t, is so that: $K_0=G\, S\, /\, t$.

Taking into account the above mentioned 140% shear strain, it means that the horizontal displacement should not exceed 1.4 t. If it is exceeded the design should be amended, for instance by supplementing the isolation system with damping devices.

For numerical applications, we consider a cuboid-shaped building (Figure 1), of length L=100 m in the X direction and width B=50 m, in the Y direction. Its roof is deemed to be high enough not to be submerged by the tsunami wave. Its mass is assumed as M=200 000 tons, which, with the above indicated design procedure and numerical values, leads to a 1974 MN/m stiffness of the bearing system, a 16 cm rubber thickness and a 22 cm acceptable displacement of the isolated building.

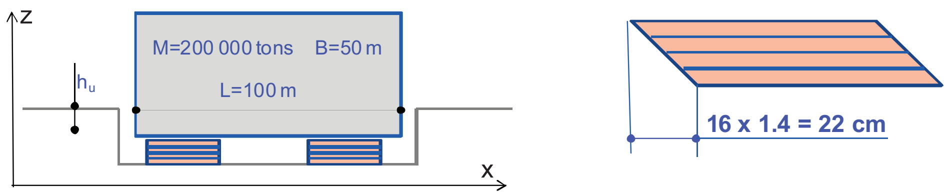

Figure 1 – Cuboid building and acceptable strain of its bearing system

LOAD CASES

Earthquake

Seismic input motion is usually represented in the form of a pseudo-acceleration response spectrum. For the purpose of our study, we consider two different input motions, both recorded in Japan, the response spectra of which are presented in the Figure 2. They practically exhibit the same PGA value of 0.67 g and very similar amplification factors, but their frequency contents are very different. The input 1, recorded at the occasion of the 2007 Chuetsu-oki earthquake shows a larger low-frequency content than the input 2 recorded at the occasion of the 2011 Big East-Japan Earthquake (BEJE). (Neither one nor the other can be regarded as having high frequency content in the usual sense of high-frequency in earthquake engineering.)

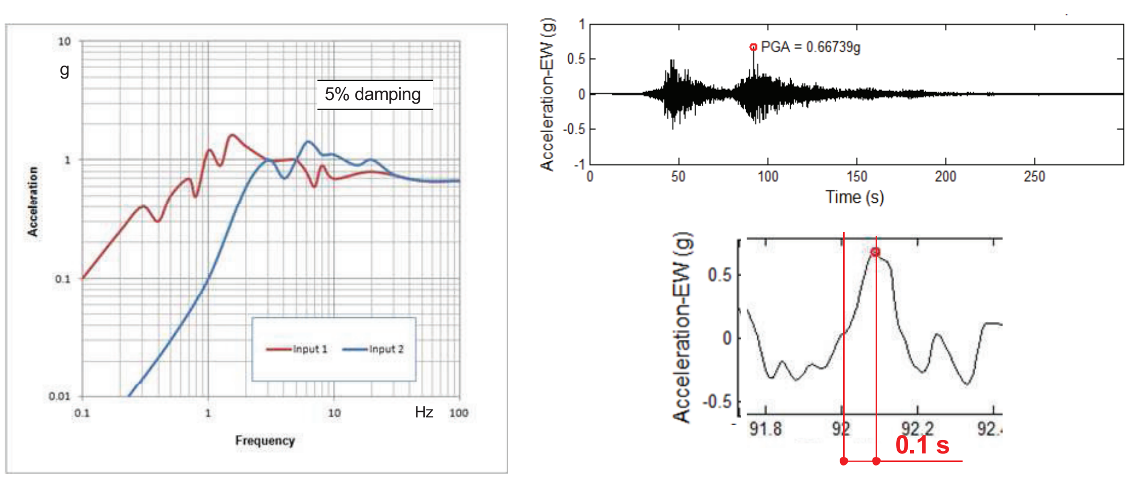

Figure 2 – Spectra of the two considered input motion (left) and time history signal of input 2

At this moment it is interesting to discuss the concept of inertia force, which is widely used by engineers as “static equivalent” force for the purpose of designing seismically safe structures. In the Figure 2 the time history record of the input 2 is also presented. An interesting point is that when the acceleration reaches its maximum value of 0.67 g, it goes from 0 to 0.67 on a period of time (around 0.1 s) that is very short compared to a seismically isolated structure eigenperiod. This is not a specific feature of this input motion but a generic one: in practice the acceleration input changes its sign several times during a period of the isolated structure. It means that, in such a situation, the concept of static equivalent inertia force does not pertain to discuss the effects of the seismic input. As a matter of fact in such a situation the seismic input motion acts as a displacement controlled load, not as a force controlled load. A consequence is that the occurrence of an input motion strong enough to generate a 350% strain in the isolation system would not result in catastrophic consequences. The bearing pads could have some damage but the supporting system would still play its role.

Tsunami

In case a building is surrounded by water (the water density is ρ=1000kg/m^3), and the water height above the ground is h, it is well known that the hydrostatic force applied on a wall of width B reads:

$$F_h = \frac{1}{2} \rho \, g \, h^2 \, B \qquad (1)$$

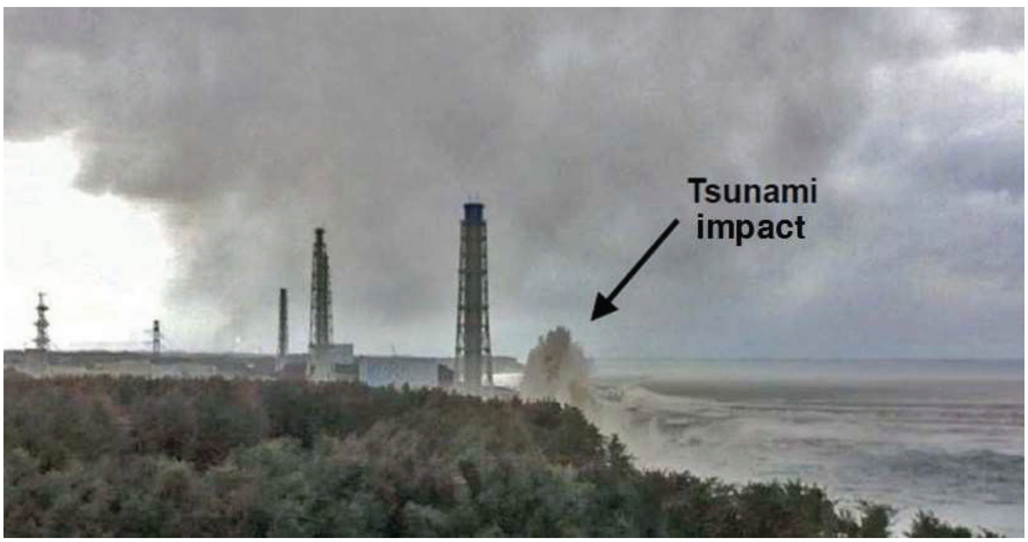

Figure 3 – Tsunami impact effect on the Fukushima Daïchi NPP. (Source: Tepco, 2011)

In the Figure 3 is presented a picture of the Fukushima-Daïchi NPP, when it was impacted by the tsunami on 2011 March 11th. It is clear on the picture that, in addition to the hydrostatic force, there is a strong dynamic effect that should be accounted for. This dynamic effect has two faces:

- The applied force is much larger than the hydrostatic force, and
- It is applied suddenly, inducing a transient effect on the response of the isolated structure.

Regarding the applied force, it depends on the velocity of the approaching wave, V_0, which velocity is related to the wave height, h, by the following formula (Robertson et al. 2011):

$$V_0 = Fr \, (gh)^{1/2} \text{ , } \; Fr \text{ being the Froude number of the flow.} \qquad (2)$$

According to Robertson et al., for those relatively flat sea shores that are prone to tsunami run-up, the Froude number is in the range between 1.5 and 2.5, and 2 can be regarded as a representative value. For numerical applications, we consider a wave height h=10 m and a Froude number *Fr*=2, which assumptions result in V_0 = 20 m/s.

In order to calculate the wave induced force, we use the momentum equation, as illustrated in the Figure 4. The basic assumption is that during the period of time dt, a wave section of length $dx=V_0$ dt is stopped. Before it is stopped, the momentum of this wave section was:

$$dp = \rho\ h\ B\ dx\ V_0. \tag{3}$$

Consequently, the wave induced force reads:

$$F_V = dp/dt = \rho\ h\ B\ V_0^2. \tag{4}$$

Eventually, the total force applied on the building can be expressed as:

$$F_H = F_h\ (1+2\ Fr^2) \tag{5}$$

This formula is another presentation of the Cross formula (Cross 1967). Robertson et al. (2011) deployed a more sophisticated approach of the tsunami induced force. However they report that their calculated forces are close to the Cross' results. In this formula, the subscript H refers the induced height of the water on the wall, resulting from the fact that a part of the kinetic energy of the wave is transformed into potential energy. The water height H reads:

$$H = h\ (1+2\ Fr^2)^{1/2} \tag{6}$$

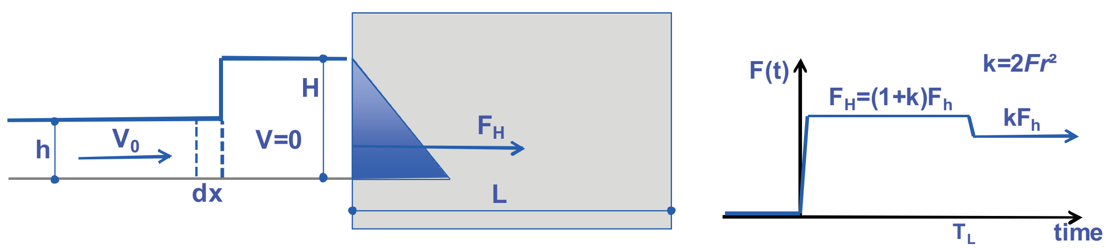

Figure 4 – Wave force calculation (left) and how it varies versus time (right)

For practical applications, considering a Froude number Fr=2 one obtains the formula (7), in which h is the height of the wave, F_h is the hydrostatic force due to this water height, H is the induced water height and F_H the induced force on the impacted wall.

$$H = 3h\ ;\ F_H = 9F_h. \tag{7}$$

After this first phase of the wave impact, the water flows along the side walls then the level of water increases at the back of the building where the hydrostatic force is eventually applied. This flow sequence last approximately for a period of time $T_L=L/V_0$. Finally the tsunami induced force can be modelled as indicated in the right side of the Figure 4.

In case the isolated structure is embedded at a depth h_u under the ground level (see Figure 1) and there is no effective preventive measure against underground inundation, it is necessary to consider that the hydrostatic pressure is increased. Taking into account this phenomenon leads to the amended following formula:

$$F_H = F_h\ ((1+h_u/h)^2+2\ Fr^2) \tag{5'}$$

At this point it is worth to mention that the tsunami induced force last for a period of time that is practically infinite in comparison to the eigenperiod of the isolated building. It means that, as opposed to the seismic load, the tsunami load should actually be regarded as a force controlled load. A consequence is that the occurrence of wave large enough to generate a 350% strain in the isolation system would have catastrophic consequences. As soon as the actual bearing capacity of some pads is exceeded, the building is at risk of being swept away by the tsunami. This is not a specific feature of a given type of isolating system, but a generic one due to the nature of the tsunami load. The only preventive countermeasure seems to be that the isolated building be sufficiently embedded in the ground.

Aircraft crash

We denote by m the mass and by v the velocity of an aircraft that is deemed to crash on the considered isolated building. We do not discuss the local effects on the impacted structure, which is assumed to be robust enough. We intend only to calculate the response of the building regarded as a rigid body implemented on the isolation system. For numerical applications, we select m=500 tons and v=150 m/s.

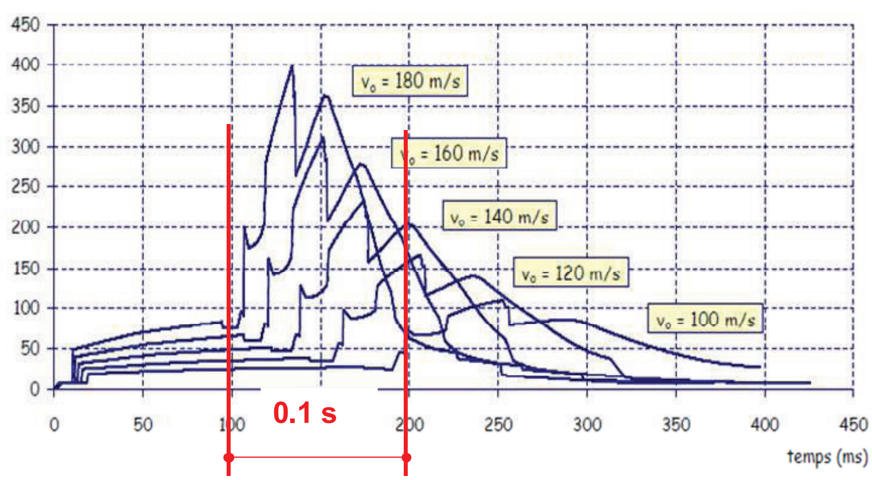

Figure 5 – Typical commercial aircraft crash load curves for different impact velocities

The mechanics of the crash was analysed by Riera (1968), who established a method that, under some conditions, enables to derive the transient force applied on the impacted building. A feature of such forces is that, for large damaging velocities, the significant part of the force lasts for only 0.1 to 0.2 seconds, as illustrated in the Figure 5. It means for a short period of time as compared to the eigenperiod of an isolated structure. Consequently, a good approximate is to consider that the effect of the crash is to move the building with an initial velocity, v_0, which can be easily derived from the momentum equation during the crash, namely M v = (M+m) v_0. Taking into account that m is very small compared to M, it results in:

$$v_0 = (m/M)\ v \tag{8}$$

We may say that, for seismically isolated structures, the aircraft crash is neither a displacement-controlled load, nor a force-controlled load; it is a momentum-controlled load. In case of a beyond design crash, susceptible to generate a 350% strain, the consequences would be more severe than for a seismic input but less than for a tsunami. Once the displacement that generates damage in the system is reached, the residual kinetic energy of the rigid body should be dissipated in the isolation system before the movement is stopped.

ISOLATED BUILDING RESPONSE

Earthquake

We denote $x_E(t)$ the response of the isolated building under a seismic input motion and x_E^{max} its maximum absolute value. Denoting $a(f_0, \xi_0)$ the pseudo-acceleration read on the specified response spectrum at the eigenfrequency f_0 (or eigenperiod T_0 in case the prescribed response spectrum is given in periods) and damping value ξ_0 of the isolated structure, x_E^{max} is calculated as:

$$x_E^{max} = a(f_0, \xi_0) /(2\pi\ f_0)^2 \tag{9}$$

In our example (f_0=0.5 Hz & ξ_0=5%) the pseudo acceleration values derived from the response spectra 1 and 2 presented in the Figure 2, are respectively a_1=0.5 g and a_2=0.03 g, which lead to x_{E1}^{max}=50 cm and x_{E2}^{max} =3 cm.

As the acceptable displacement is 22 cm, we conclude that the proposed isolating system is suitable for the input 2 but not for the input 1. In order to make it acceptable for the input 1, it should be supplemented by damping devices designed to provide approximately a total 40% damping. This estimate comes from the extrapolation formula (10), which is useful in case the specified response spectrum does not cover the range of large damping values.

$$a(f, \xi)= a(f, \xi_0) / (\xi/ \xi_0)^{0.4}. \tag{10}$$

Tsunami

Would the F_H force be applied statically, the displacement response of the isolated building would be simply calculated by any of the following equivalent formulae:

$$x_S = F_H/K_0 = F_H/M\ 1/(2\pi f_0)^2 = F_H\ T_0^2/ 4\pi^2\ M \tag{11}$$

For a Heaviside type of input such as presented in the Figure 4, the ratio of the dynamic response, $x_D(t)$, to the static one, x_S, reads as per the formula (12) (for $t<T_L$). It is plotted in the Figure 6 for 5% damping.

$$\frac{x_D(t)}{x_S} = 1 - e^{-\xi_0 \omega_0 t}(\cos \omega'_0\, t + \frac{\xi_0}{\sqrt{1-\xi_0{}^2}} \sin \omega'_0\, t) \quad , \quad \omega'_0 = \omega_0 \sqrt{1-\xi_0{}^2} \tag{12}$$

The maximum value of $x_D(t)/x_S$ (often designated as the amplification factor) can be derived from the above formula. It is well known that in case of no damping, the amplification factor value is 2. For small damping values, the first order estimate is given by the formula (13). For other damping value see the Table 1.

$$x_D^{max}/x_S=2-\pi\xi_0. \tag{13}$$

According to the above selected numerical data, the F_H value, based on formula (5), is F_H = 225 MN. Consequently, the static response of the building is an x_S=11.4 cm displacement. For a 5% damping, the maximum response can thus be estimated as x_D^{max}=21 cm, what is just acceptable.

The key point here is that situations may be encountered, for which neglecting the transient effect resulting from the sudden impact of the wave could lead to the conclusion that an isolation system is appropriate, while the opposite conclusion should be drawn.

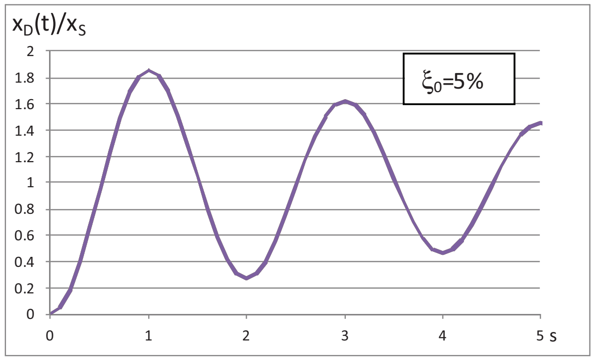

Figure 6 – Ratio of the dynamic response to the static response under tsunami load

Table 1 – Amplification factor under tsunami impact

ξ_0 %	0	5	10	15	20	30	50	70	100
x_D^{max}/x_S	2	1.85	1.73	1.62	1.53	1.37	1.16	1.05	1

In the above calculation, we assumed that the "narrow" side of the building was exposed to the tsunami impact. Would we assume that the building is implemented in such a way that its large side is exposed to the wave, the conclusions would be dramatically different: The F_H force would be multiplied by a factor 2 and consequently we would obtain x_S=22.8 cm and x_D^{max}=42 cm Theoretically x_D^{max} could be reduced down to x_S by supplementing the bearing system with sufficient damping devices so as to reach the critical damping (ξ_0=100%). (It should be noticed that damping devices do not have obviously any effect on x_S.). It means that a possible implementation of additional damping devices would anyway be useless to meet the design criterion. In such a case, the safety of the installation would rely on the beyond 140% shear strain robustness of multilayer bearing pads. Taking into account the margins encompassed in the design criterion this could be possibly acceptable in case the wave under consideration is regarded as a beyond design wave.

Aircraft crash

Under the initial velocity v_0 resulting from the aircraft crash, derived from the formula (8), the response $x_A(t)$ of the isolated building, plotted in the Figure 7, reads:

$$x_A(t) = \frac{v_0}{\omega'_0} e^{-\xi_0 \omega_0 t} \sin \omega'_0 t \,. \tag{14}$$

For small damping values (up to 20%), the first order estimate of x_A^{max} reads:

$$x_A^{max} = (1/2\pi - \xi_0/4)\, v_0 T_0. \tag{15}$$

With the above selected numerical data, the initial velocity resulting from the crash is v_0=0.375 m/s. For a 5% damping of the isolation system, the induced displacement is x_A^{max}= 11 cm.

For damping values that cannot be regarded as small, the value of x_A^{max}/v_0T_0 is given in the Table 2.

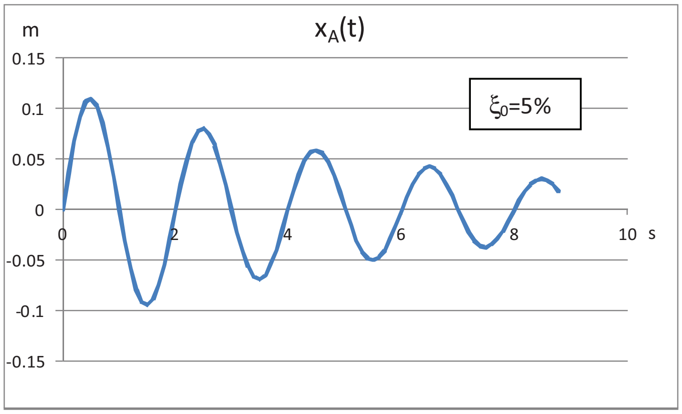

Figure 7 - Response under aircraft crash for the selected numerical data

Table 2 – Non dimensional response to an aircraft crash

ξ_0 %	0	5	10	15	20	30	50	70	100
$x_A^{max}/v_0 T_0$	0.16	0.15	0.14	0.13	0.12	0.11	0.087	0.072	0.058

CONCLUSIONS

In this paper we have presented simple methods that enable to calculate the response of a base-isolated massive structure under seismic strong motion, tsunami and aircraft crash. We have illustrated the methods by numerical applications of the proposed formulas.

For the seismic strong motion, the required input data consists of a conventional response spectrum. For the tsunami, the only required input data is the wave height. The wave velocity velocity is derived from the representative value of the Froude number, *Fr*=2. In case the encountered situation suggests another *Fr* value, the formula (5) applies. For the aircraft crash, the only required input data are the mass and velocity of the aircraft.

Under these three types of loads, the isolated structure response is a transient function of time. Its maximum value is directly derived, by definition, from the response spectrum under seismic input. It results from the formula (13) under tsunami and from the formula (15) under aircraft crash. These two formulas are valid for small (say less that 10%) damping values. For larger values the maximum can be numerically derived from the formulas (12) and (14).

A key point of the above presented analyses is in the anticipated consequences of a beyond design situation. In all cases there are significant margins in the design criterion on acceptable shear strain. However, would the actual ultimate capacity be reached, the consequences would be dramatically different, depending on the load case under consideration:

- A significant beyond design ground motion could result in some damage in the isolation system, without severe consequences for the isolated structure.
- On the contrary, a significant beyond design tsunami can rapidly degenerate in a catastrophic situation.

- A significant beyond design aircraft crash is an intermediate case.

This conclusion results from the dynamics of such low-frequency isolated systems. For such systems, the seismic input motion acts as a displacement controlled load, while the tsunami acts as a force controlled load (this is always the case, not only for low-frequency isolated structures) and the aircraft crash as a momentum controlled load.

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