Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Sliding response spectrum for the design of nuclear polar cranes

H. Noé & P. Labbé
EDF, Engineering and Construction Division, Basic Design Department, Villeurbanne, France

ABSTRACT : This paper deals with the seismic behaviour of sliding structures such as cranes. In industrial facilities which have experimented strong earthquakes, this kind of equipment has demonstrated a rather good behaviour, whatever the amplitude of the ground motion was.
In the present design practice of these equipments, sliding effects are not considered. Results obtained with classical elastic analysis are consequently overestimated and some difficulties may arise when trying to meet basic requirements for seismic loadings.
The aim of the study presented in this paper is to show that, considering the dynamic characteristics of the structure, a simplified model may be defined to estimate the seismic response and to develop a design method analoguous to the classical response spectrum analysis.

1 INTRODUCTION

In nuclear power plants large-size overhead traveling cranes, such as the reactor polar crane, are used to transfer heavy loads. Often installed on top of buildings, the crane has then to be designed for strong seismic loads.

In the classical design practice, using the elastic response spectrum method, some difficulties may arise when trying to meet basic requirements, due to overconservative results.

Unlike other equipments anchored to the buildings, the crane is able to slide on its supports (runway rail) when seismic forces reach the yield friction forces. The first consequence of this is a substantial reduction of accelerations transmitted to the crane.

Different works such as those done by Mostaghel and Tanbakuchi (1983) or Constantinou and alii (1984) in a seismic isolation purpose have shown that taking account of sliding effect was very interesting to reduce design seismic loads, even if the adverse consequence of sliding is an increase of differential displacement between the equipment and the supporting structure.

The aim of this paper is to present the main results of a parametric study and to propose a sliding spectrum for the design of nuclear cranes.

2 PROBLEM DEFINITION

2.1 Sliding oscillator model

The system, as shown in Figure 1, represents the structural model used in this study. It is composed of a primary structure (i.e. the building) and a secondary structure (i.e. the sliding equipment).

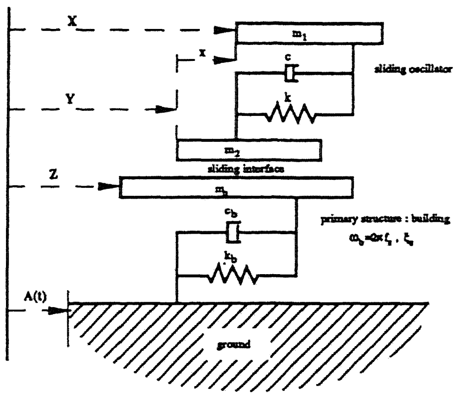

Figure 1 : Model of the sliding oscillator.

The primary structure is modelled by a linear damped spring-mass oscillator characteristics of which are chosen so that dynamics properties, natural frequency f_b and damping ratio ξ_b, be scaled on typical values of nuclear building first eigenmode. By this way, it is possible to take account for the well-known filtering effect of supporting structures. In this model, the value of mass m_b is considered as sufficiently higher than the one of the sliding equipment in order to eliminate coupling effect between the primary and the secondary structures.

The secondary structure, i.e. the sliding equipment itself, is modelled by a 2 DOF system. It represents the behaviour of the crane for a seismic motion in a horizontal direction perpendicular to the beams of the crane In that direction one may consider that the crane may freely slide.

In this model, masses m_1 and m_2 are connected through a linear spring-damper system accounting for the properties of the first eigenmode of actual cranes.

Such a simplified model of a sliding equipment is justified by the fact that nuclear traveling cranes usually present a low-frequency first mode typically between 2 and 3 Hz. For this mode, the participation factor is high (between 60 and 90 % of the total mass of the structure).

2.2 Dynamic equations of motion

To derive dynamic equations in slip and non-slip mode, different assumptions are made.

i) Static and dynamic friction coefficients are assumed to be equal,
ii) No coupling effect between the sliding equipment and the building,
iii) Effects of vertical seismic motion and effects of horizontal seismic motion on support reactions are not considered.

If T and N are respectively the tangential and normal forces acting on mass m_2, the non-sliding condition for a Coulomb's law of friction writes :

$$T \leq \mu N \qquad (1)$$

where $N = mg = (m_1+m_2)g$

In eq. 1, μ represents the equivalent coefficient of friction. It is often different from the physical value of the friction coefficient at the contact point between the wheels and the rail.It has to take account for the effective number of sliding wheels and for the eventual presence of a rated load.

Classicaly, the expression of the tangential force T may be written as follows :

$$T = m_1\ddot{X}(t) + m_2\ddot{Y}(t) \qquad (2)$$

where X and Y are the absolute displacements of masses m_1 and m_2 respectively.

During non-slip mode, mass m_2 is sticking to its support. So,

$$Y(t) = Z(t) \qquad (3)$$

Finally, the expression of the non-slip condition may be derived and reads,

$$|\alpha\ddot{x} + \ddot{Z}| < \mu g \qquad (4)$$

In this relation, x(t) is the displacement of mass m_1 relatively to mass m_2, and α is defined as :

$$\alpha = \frac{m_1}{m_1 + m_2}$$

If the condition (4) is verified, the dynamic equilibrium is provided by :

$$\ddot{x}(t) + 2\xi_0\omega_0\dot{x}(t) + \omega_0^2x(t) = -\ddot{Z}(t) \qquad (5)$$

where ω_0 and ξ_0 represent the dynamic properties of the fixed-base oscillator.

$$\omega_0^2 = \frac{k}{m_1} \quad \text{and} \quad \xi_0 = \frac{c}{2\omega_0 m_1}$$

As soon as the tangential force T reaches the limit value of friction, the mass m_2 begins to slip on its support and is only subjected to this force. Then,

$$|T| = \mu N$$

or

$$\alpha\ddot{x}(t) + \ddot{Y}(t) = -\mu g \,\text{sign}(\dot{Y}-\dot{Z}) \qquad (6)$$

The dynamic equilibrium (5) still holds if, in the right part of this equation, the absolute displacement Z of mass m_b is replaced by the absolute displacement Y of mass m_2. Then,

$$\ddot{x}(t) + 2\xi_0\omega_0\dot{x}(t) + \omega_0^2x(t) = -\ddot{Y}(t) \qquad (7)$$

Mixing eq.(6) and (7) leads to,

$$\ddot{x}(t) + 2\xi_g\omega_g\dot{x}(t) + \omega_g^2x(t) = \frac{\mu g}{1-\alpha}\text{sign}(\dot{Y}-\dot{Z}) \qquad (8)$$

In the above equation, ω_g and ξ_g respectively represent the pulsation and damping ratio of the sliding oscillator. They are defined as follows :

$$\omega_g^2 = \frac{\omega_0^2}{1-\alpha} \quad ; \quad \xi_g = \frac{\xi_0}{\sqrt{1-\alpha}}$$

2.3 Resolution

Considering the non-linearity due to the friction interface, the time-history response of the sliding structure is obtained by means of a step-by-step algorithm developed for this purpose. During each phase of the motion (slip or non-slip), the dynamic equation of motion is such that the second part of the equation is a linear function of time and Westermo and Udwadia (1983) have proposed formal solutions that we have used in this study. Validations have been made by comparisons with analytical solutions in the case of harmonic excitation.

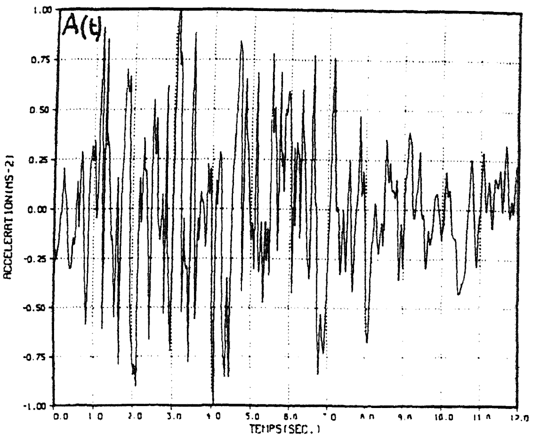

Figure 2 : ground motion accelerogram

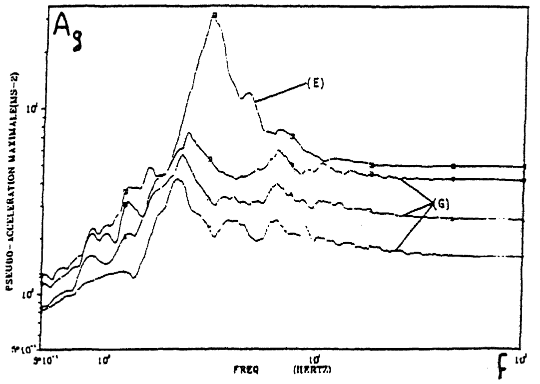

Figure 3 : Example of sliding spectra

3 SLIDING SPECTRUM

3.1 Definition

As previously said, it is possible to obtain the response x(t) (relative displacement of mass m_1) to a given earthquake motion A(t) and for a sliding oscillator characterized by the following parameters :

- the pulsation ω_0 of the fixed-base oscillator ;
- the associated damping ratio ξ_0 ;
- the mass ratio $\alpha = m_1/m$;
- the equivalent friction coefficient μ.

From the calculated response, only the maximum value x_{max} is retained. The same procedure is then applied to a wide range of frequencies and for various values of the abovementioned parameters.
This set of curves is named the displacement response spectrum of sliding oscillators subjected to A(t).
As for the classical linear oscillator, the sliding response spectrum may be defined in terms of its absolute pseudo-acceleration A_g such that,

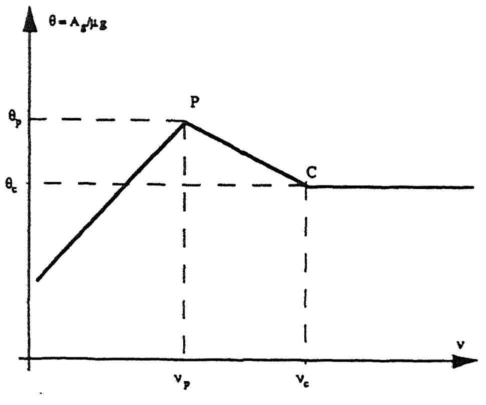

Figure 4 : Adimensional sliding spectrum

$$A_g = \omega_0^2 \, x_{max} \tag{10}$$

In Figure 3 such a typical sliding spectrum is represented. In this case, the ground motion is an accelerogram which response spectrum fits the NRC design spectrum. This ground motion is filtered by the building characterized by its natural frequency and its damping ratio, 3 Hz and 5% respectively.The level of excitation of mass m_b is scaled at 0.5 g. Parameters of the sliding oscillator are : mass ratio $\alpha = 0.6$, damping ratio $\xi_0 = 4\%$ and $\mu = 0.06$, 0.1 and 0.17.

3.2 Adimensional sliding spectrum

It can be shown that the sliding spectrum may be displayed in terms of adimensional coordinates and that the sliding spectrum may be transformed into a Adimensional Sliding Spectrum (ASS) in which the coordinates are defined as follows.
The x-axis is defined by the ratio of the natural circular frequency ω_0 of the fixed-base oscillator and the natural pulsation ω_s of the supporting structure. Then,

$$\nu = \omega_0/\omega_s$$

The y-axis is defined as the ratio θ between the maximum acceleration A_g of mass m_1 and μg.So,

$$\theta = A_g/\mu g$$

The general shape of the ASS is represented in Figure 4.

It has be shown by Westermo and Udwadia (1983) that the response of the oscillator was controlled by the adimensional parameter η defined as the ratio between the maximum acceleration $A_b = Z_{max}$ of the supporting mass m_b and μg.
As indicated in Figure 4, the ASS exhibits an asymptotical value when ν goes to infinity. Because of non-linear behaviour, it is difficult to speak of a cut-off frequency over which no amplification appears. In this case, the pseudo cut-off frequency has to be regarded as the one over which the acceleration is quasi constant, even with a small amplification.

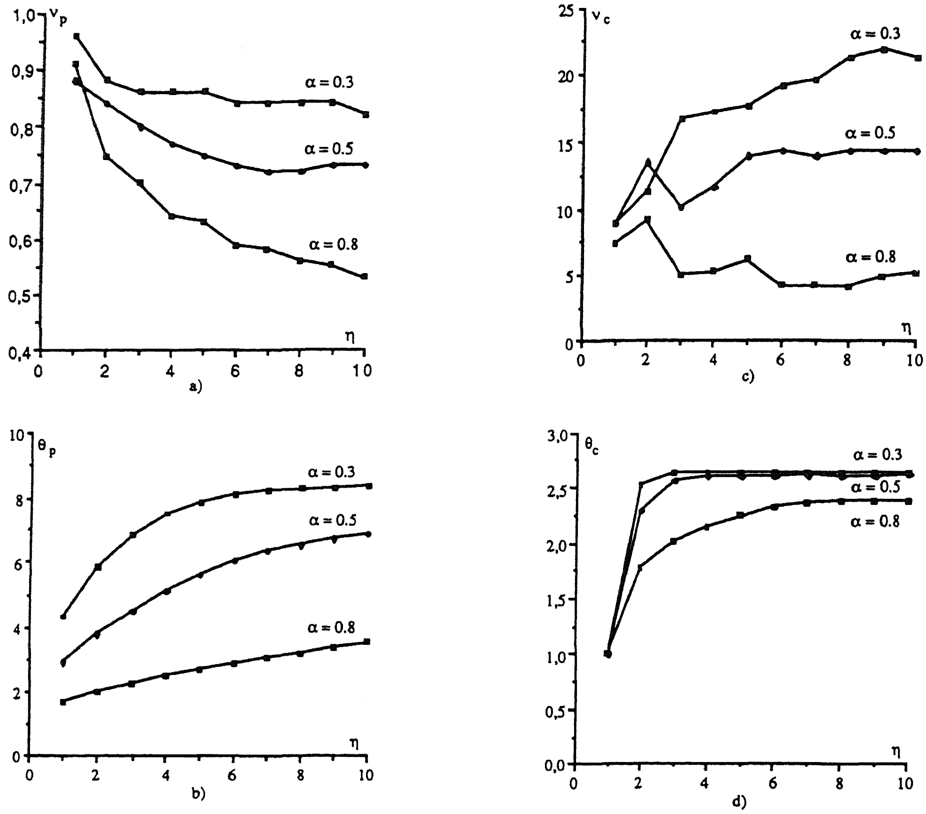

Figure 4 : influence of the adimensional level η

It has been demonstrated by Betbeder-Matibet &alii (1992) that a closed-form expression of the pseudo asymptotical value was :

$$\theta_{limit} = 3 - 2\pi\xi_g \quad \text{when } \nu \to \infty \qquad (11)$$

3.3 Sensivity analysis

Here we present the main results of a sensivity analysis performed upon numerical simulations. As shown in Figure 4, the interest is focused on the variations of the two significant points of the ASS : $P(\nu_p,\theta_p)$ and $C(\nu_c,\theta_c)$.

The values of the different parameters are defined as follows.

- the time-history ground motion is A(t) represented in Figure 2 ;
- ξ_0 varies between 4 and 7% ;
- the adimensional level of excitation η varies between 1 and 10 ;
- the mass ratio α varies between 0.1 and 0.9 ;
- the natural pulsation ω_b of the supporting structure varies between 2π and 12π.

The choice of these bound values has been determined to cover the practical domain in which the sliding spectrum is expected to be used.

3.3.1 Influence of the adimensional level of excitation η

In Figures 5.a to 5.d are represented variation curves of the coordinates of the two significant points P and C for three values of the mass ratio α : 0.3, 0.5 and 0.8.

From these results, it can be seen that :

- in a general manner, for η sufficiently high (>4) the variations of the coordinates of P and C become almost linear ;
- About the variations of θ_c (Figure 5.d), it can be seen that, for high levels of excitation, θ_c tends to an asymptotical value close to the theoritical estimation provided by formula (11).

As an example, for ξ_0 and α equal to 5.5% and 0.3 respectively, eq. 11 provides a value of 2.6 close to the simulation results.

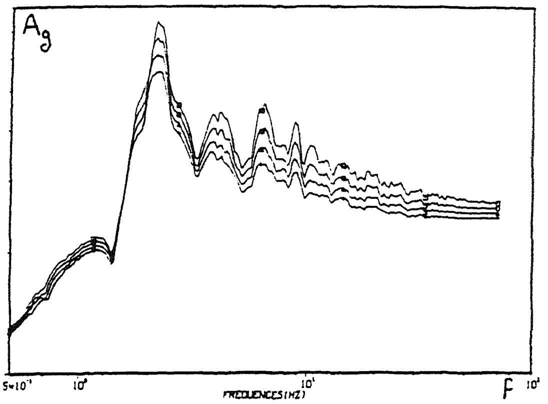

Figure 6 : influence of the damping ratio ξ_0

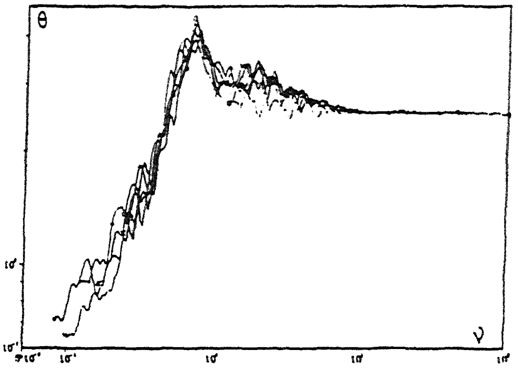

Figure 7 : Influence of the pulsation ω_b

3.3.2 Influence of the damping ratio ξ_0

In Figure 6 are represented the sliding spectra calculated for 4, 5, 6 and 7% of damping. The influence of the damping ratio ξ_0 of the fixed-base oscillator may be summarized as follows :

- the general shape of the sliding spectrum is not modified when ξ_0 varies, i.e. principal and secondary resonant peaks are maintained ;
- the pseudo-acceleration varies as the ratio $1/\sqrt{\xi_0}$ with good correlation ;
- for higher frequencies, the acceleration is still damping ratio dependant and comfirm the fact that, in this case, the cut-off frequency notion does not hold anymore.

3.3.3 Influence of the pulsation ω_b

As shown in Figure 7, the general shape of the ASS is practically unchanged when ω_b varies between 2π and 12π. This confirms that the sliding spectrum can be presented in an adimensional form along x-axis.

4 APPLICATION TO THE DESIGN OF NUCLEAR CRANES

From the parametric study which results have been presented, a specific sliding spectrum can be derived for the design of sliding equipment such as overhead cranes.

For this purpose, some simplifications have been introduced in order to provide an easy-to-use curve for designers. Three steps have been defined to obtain this design spectrum.

i) From the ASS presented in Figure 4, coordinates of points P and C are calibrated for specific conditions (site, buildings, friction interface and equipment). The values of the coordinates of P and C are obtained by using the results of the parametric study presented in Figures 5.a to 5.d.

ii) In the second step, the sensivity of both frequential parameters ν_p and ν_c to the variations of η and α are interpreted in terms of spectral broadening. Considering that for structures such as overhead cranes, typical values of α lie in the range 0.6-0.8 by comparison with the effective modal mass ratio of the first mode, the ranges of variation of ν_p and ν_c can be derived. This leads to the Adimensional Design Sliding Spectrum (ADSS) such as the one presented in Figure 8. This last simplification tends to limit the control parameters to θ_p and θ_c and to account for uncertainties involved in the ground motion representation.

iii) The last step consists in applying site and friction interface conditions to finally obtain the design sliding spectrum in physical coordinates by means of the following transformations :

$$\nu * f_s \longrightarrow f \quad \text{and} \quad \theta * \mu g \longrightarrow A_g$$

It is important to note the the resulting design sliding spectrum is derived for a specific value of the model friction coefficient μ. This means that for any other value of μ, the same procedure has to be followed again.

In the practical design of polar cranes, designers have to pay particular attention to the influence of the rated load. One possible way is to modify the friction coefficient as follows :

$$\mu' = \mu\left(1 + \frac{W_r}{W_0}\right) \qquad (12)$$

where W_0 and W_r represent the dead weight of the crane and the rated load respectively.

As in the classical response spectrum method, the sliding spectrum as so defined may be used as the seismic input in the direction where the sliding is permitted.

A particular attention has to be made for the choice of limit conditions at support points (sliding and non-sliding wheels). The validity of the results largely depends on it.

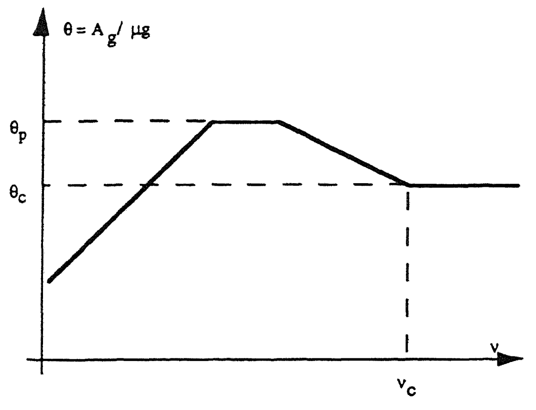

Figure 8 : Adimensional Design Sliding Spectrum

5 CONCLUSIONS

In this paper, a simple oscillator model has been used to analyse the behaviour of a sliding structure submitted to a seismic ground motion filtered by a building.

The main feature of this model is that it enables to introduce the flexibility of the sliding structure, such as a polar crane, which increases the reduction of accelerations transmitted to the crane.

From the results presented in this paper, main conclusions are as follows.

i) The response of a sliding oscillator may be derived in an adimensional form (ASS). It only depends on the adimensional level of excitation, the mass ratio and the damping ratio of the fixed-base system.

ii) For specific conditions (e.g. polar cranes), it i proposed a design sliding spectrum (ADSS) to be used in place of the classical elastic response spectrum.

iii) To take account for the rated load, a possible way is to define an equivalent friction coefficient.

Nevertheless, comparisons with actual sliding structures have to be made to assess the validity of this approach and to verify the existence of sufficient margins.

REFERENCES

Mostaghel, N. and Tanbakuchi, J. 1983 Response of sliding structures to earthquake support motion. *Earthquake Engineering and Structural Dynamics*, 11:729-748.

Constantinou, M.C., Gazetas, G. and Tadjbakhsh, I. 1984 Stochastic seismic sliding of rigid mass supported through non-symmetric friction. *Earthquake Engineering and Structural Dynamics*, 12 : 777-793.

Westermo,B. and Udwadia,F. 1983 Periodic response of sliding oscillator system to harmonic excitation. *Earthquake Engineering and Structural Dynamics*,11:135-146.

Betbeder-Matibet, J., Pons, J.C., Labbé, P. and Noé, H.Seismic response of sliding structures and equipment. *Recent Advances in Earthquake Engineering and Structural Dynamics*. Paper V-3. Coordin. editor Davidovici V. Ouest Editions.