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Multi-mode factor for motor-driven pump units: compared pseudo-static and dynamic (response spectrum and time history) determination of seismic loads at anchorage points

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ABSTRACT

In the framework of the seismic verification of plant equipments, the determination of the seismic loads applied to motor-driven pump anchorages is optimized. A rough justification is usually first performed using the 1 degree-of-freedom pseudo-static analysis, including a 1.5 multi-mode factor. The question is asked about the relevance of the multi-mode factor value, by comparison to dynamic response spectrum and time history analyses, considered as reference methods. Two motor-driven pump units are considered: seismically flexible with vertical axis and stiff with horizontal axis; the quantities of interest are the shearing and tearing loads at anchorage points.

Actual 3D floor response accelerograms, issued from nuclear unit building response to ground seismic excitation, are used. In order to take into account the statistical seismic characteristics, 9 independent seismic loads have been applied and the average maximal time history response could be determined.

On the most loaded anchorages, ratios larger than 1.5 can be exhibited both on the two motor- pump units, either using SRSS or Newmark direction combination, authorizing to decrease the multi-mode factor from 1.5 to 1 for the determination of seismic loads at anchorage points of this type of mechanical systems.

INTRODUCTION

The motor-driven pump units are designed so that they can resist without damage to seismic excitations: stability, integrity and functionality must thus be saved during and after the earthquake. In the case of the seismic verification of an installed motor-driven pump unit, since the soil excitation levels considered during decennial visits in nuclear industry are higher and higher, the objective is to perform more realistic simulations of resulting loads applied to anchorages, compared with those carried out for design purpose. Two ways are so followed: optimize the excitation loads and optimize the determination of the equipment response.

The purpose of the paper concerns the influence of the methods used to determine the resulting inertial seismic loads at equipment anchorages, typically the equivalent static method by comparison with the response spectrum and the time history analyses, here considered as the reference methods. Two different motor-driven pump units are studied: flexible with vertical axis and stiff with horizontal axis. The quantities of interest are the shearing and tearing loads, deduced from seismic resulting loads at anchorage points.

Principles of the three seismic equivalent static, response spectrum and time history analyses are presented, with their application on motor-driven pump units. The one-degree-of-freedom pseudo-static method is usually applied to early design the motor-driven pump units with no needs to elaborate a finite element model; a multi-mode factor is then associated to ensure conservatism. Using a finite element model, linear response spectrum analysis is widely used to design and justify buildings and equipments regarding seismic risk. It allows the probable mean maximum response of scalar quantities of interest (acceleration, displacement, stress, force, moment) due to seismic excitation, which is represented by directional floor response spectra. Based on the statistical responses to several accelerograms, obtained via direct resolution of dynamic equations, time history analysis is the most representative analysis.

Comparative response spectrum vs pseudo-static studies on simple dynamical systems (see Nichoff and Gürbüz (2007), Parulekar et al. (1999) and White et al. (2007)) have been performed, completed with similar studies on motor-driven pump units, see Audebert and Rousseu (2019): they concluded that 1.5 multi-mode factor could not be surely decreased, based on the reference response spectrum results. Complementary comparative seismic time history analyses are here carried out, considered as the new reference dynamical seismic results. Recommendations are then given about the relevancy of the 1.5 multi-mode factor value for motor-driven pump units.

THEORETICAL BACKGROUNDS

Types of seismic analyses

Seismic analyses used in the design of nuclear safety-related structures are usuaally conducted using linear, methods, under elastic behavior assumption. In some cases, nonlinear or inelastic seismic analyses may be conducted to obtain more realistic results. Two types of linear elastic methods are commonly used: equivalent static and dynamical methods. Among dynamical methods are response spectrum and linear time history analyses, with the seismic input motion respectively represented by floor response spectrum, and floor acceleration, velocity and displacement, functions of time.

The pseudo-static method

Literature review

Principle

The pseudo-static method (or Static Coefficient Method SCM, or Equivalent Static Method ESM, or Equivalent Static Lateral Force Method) is a simplified seismic analysis, that represents the effect on a system, structure, component SSC or equipment, of a seismic input motion by an equivalent static force F, determined by applying a uniform acceleration $A_{\max}$ to the mass m of the SSC (see Equation 1):

$$F = \alpha m A_{\max} \tag{1}$$

The acceleration can be applied either at the SSC gravity center, as a punctual force, or on a finite SSC element model, represented by its mass matrix.

The dynamic amplification factor α (or multi-mode factor or Equivalent-Static Load Factor (ESLF), see White (2007), is applied to take into account the multi-frequency input motion and the multi-modal SSC characteristic, to prevent from possible unfavorable dynamic combinations.

Multi-mode factor

A 1.5 multi-mode factor have been currently used for practical application of the pseudo-static method since 1976. NRC has recommended the 1.5 value since 1981, see USNRC (2013). Number of studies have been performed in order to justify or reduce this value, see Nichoff (2007).

Application domain

Geometry: in IEEE, USNRC and ASCE codes, the pseudo-static method is only recommended for structures that can be simply modelled (regular horizontal and vertical geometry, equal distribution of mass and stiffness, symmetry so that torsional movement is avoided).

Dynamical behavior: the system is assumed to respond on its fundamental eigenmode. The method is applicable if its vibrational behavior is not affected by modes, in every principal directions, with eigenfrequency greater than the fundamental one, see Encyclopedia of Earthquake Engineering (2013). The method is recommended for systems whose vibrational behavior is not far from a cantilever or clamped-free beam behavior, see Parulekar (1999).

Conservatism

The conservatism of the pseudo-static method, with 1.5 multi-mode factor, is evaluated by comparison with dynamical seismic analysis methods, generally the response spectrum method.

Non conservatism can be observed in case of:

- dynamical systems with more than 2 resonancies in the amplification domain of the seismic excitation spectrum, see Parulekar (1999);

- dynamical systems with local eigenmodes not far from global modes, whose eigenfrequencies are near the peak excitation frequency; typically, not use the method if the ratio between local and global eigenfrequencies is between 0.5 and 3, see American Society of Civil Engineers (2014).

Practical application to nuclear safety-related pump units

Comprehensive methodology for nuclear safety-related equipements

For each direction, the spectral accelerations are determined from floor response spectra, at support elevations. The same input seismic motion is applied to all the supports.

The spectral accelerations to be used are peak spectral acceleration if the modal SSC characteristics are unknown, or zero-period acceleration ZPA in case of seismically rigid equipment, or spectral acceleration at fundamental SSC frequency in case of seismically flexible equipment.

Equivalent static force is applied the SSC gravity center (the equivalent static method is named 1 degree-of-freedom pseudo-static method in this case). The α multi-mode factor value is generally taken as 1.5. Total response is obtained using quadratic or 100-40-40 Newmark directional combinations.

Determination of quantities of interest of nuclear safety-related pump units

The quantities of interest are the shearing and tearing loads, deduced from seismic loads at anchorage points. The three directional components of seismic inertial loads induced at the SSC gravity center are first determined using Equation 1. The seismic effort torsor $(F_X, F_Y, F_Z, M_X(O), M_Y(O), M_Z(O))$ at the geometrical center O of the anchorages can then be deduced. After distribution of torsor components on bolts, under the assumptions of undeformable solid that authorises the application of static fundamental principle, and identical elastic anchorage behaviour, total seismic shearing and tearing loads can thus be calculated, depending on the number and location of bolts.

The linear elastic response spectrum analysis

Principle

Based on a finite element SSC model, linear response spectrum analysis allows the probable mean maximum response of scalar quantities of interest (acceleration, displacement, stress, force, moment) due to seismic excitation, which is represented by directional floor response spectra. It is based on the combination of individual modal responses. To ensure an adequate representation of the equipment dynamical response, all the eigenmodes with frequencies less than the zero-period acceleration (ZPA) frequency (and no more) should be included. The residual rigid response should be systematically addressed and quadratically combined with the modal response combination. Acceptable procedures for combining modal responses include the complete quadratic combination (CQC) method and others that account for the correlation between closely spaced modes. In case of seismically stiff dynamical system, the response spectrum result is but composed of the residual rigid response. When using 3D individual earthquake components (two horizontal and one vertical directions), the directional responses should be combined, at the last step, either by the SRSS or the Newmark's methods.

The linear time history method

The linear time history method, either on physical or modal basis, consists in the resolution of the fundamental equation of dynamics. Applied to seismic field, a particular attention must be paid on the variability of results, depending on sets of accelerograms applied: the use of at means 3 independent sets of directional accelerograms is thus required. Maximal temporal quantities of interest are then utilized.

Application to pump shearing and tearing load determination

The resulting of the nodal reactions is calculated for each anchorage and each direction: F_X , F_Y and F_Z .

Total shearing load F_{Htotal} can be deduced using:

$$F_{Htotal} = \sqrt{{F_X}^2 + {F_Y}^2} \tag{2}$$

Total tearing load simply is:

$$F_{Ztotal} = F_Z \tag{3}$$

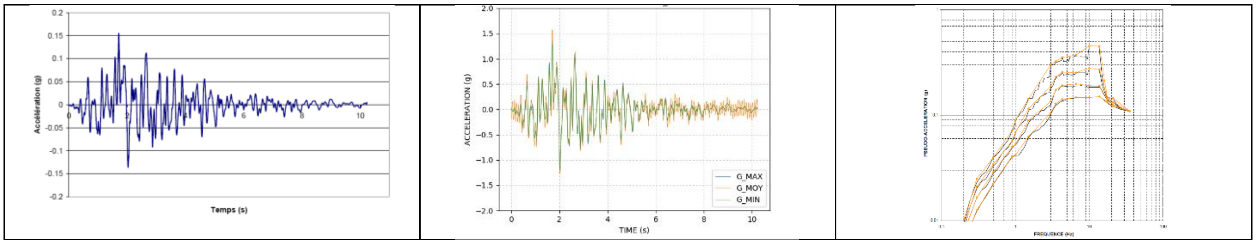
Comparison methodology

The methodology of equivalent static and dynamical responses comparison is based on shearing and tearing reactions at anchorage points. Only force components are compared: moments relatively to the center of anchorages issued from response spectrum simulations are not used for comparison because these moments are not provided by the equivalent static method. Time history response finally used corresponds to average maximal responses to 9 independent floor accelerograms.

APPLICATION TO THE DYNAMICAL PUMP UNIT MODELS

Seismic excitation

To take into account the statistical characteristics of response spectrum response, 9 seismic floor set of accelerograms in the three directions are issued from building time history responses to seismic ground motion, at the floor where the pump units are located, from 9 independent synthetic ground accelerograms, relatively to 3 ground types and 3 directional permutations (Figure 1). The floor spectral pseudo-accelerations are then determined by average on permutations, envelope on grounds, frequency broadening and smoothing operations (Figure 1). The spectral zero-period pseudo-acceleration is 35.5 Hz; reduced damping value considered is 5%.



Ground accelerogram (example)	Floor accelerograms (example)	Vertical floor spectral pseudo-acceleration

Figure 1: Seismic ground and floor motions.

The finite element pump unit models

Two different motor-driven pump units are considered:

- a seismically stiff pump unit, with horizontal axis;
- a seismically flexible pump unit, with vertical axis.

Components are simply represented, including suction and delivery pipes after their first supports, so that the first eigenmodes can be represented with satisfactory accuracy, in comparison with experimental modal characteristics. The connections between components are represented either thanks sticked surfaces or stiffness elements; their values are updated so that they fit the pump eigenmodes in the bandwidth of interest. The corresponding finite element meshes are illustrated on Figure 2.

The horizontal stiff pump unit

Components of the horizontal-axis pump unit are the pump, bearing, coupling, motor, mounted on a metallic frame, solidary with a concrete slab: the whole system is about 1 meter long.

Boundary conditions are clamping at 4-screw locations under the frame. The seismic loads at anchorages are determined as the resultant force on the application 0.07 m-diameter discs for screws on motor and pump.

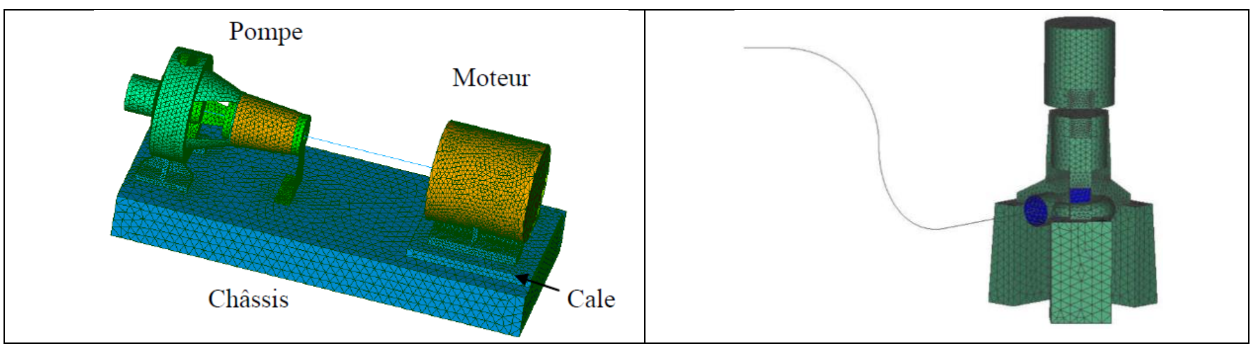


Figure 2. Horizontal and vertical motor-pump units.

The vertical flexible pump unit

The vertical-axis pump unit is composed of the pump, bearing support, motor at high part, mounted on three concrete studs on low part. The base of the three studs is clamped. The seismic loads at anchorages are determined as the resultant force on the higher stud faces.

Modal characteristics

The modal characteristics of the two pump units are presented in Table 1. The first eigenmodes of the horizontal pump unit only concern the pipe, in accordance with its stiff behavior; the first eigenfrequency concerned with the pump unit itself is 65.9 Hz, largely beyond the zero-period acceleration. Concerning the vertical flexible pump unit, two pump eigenmodes can be identified in the amplification area of the floor seismic excitation. Model parameters could be updated so that these two numerical flexion eigenmodes well represent the measured corresponding modes (0.9 MAC criterion about and 2.5% frequency gap); cumulative modal mass is less than 40% of the total mass in each direction, because the studs do not participate to the movement.

Table 1: Modal characteristics of the pump units in [0 Hz; 35.5 Hz] frequency bandwidth

	Horizontal stiff pump unit		Vertical flexible pump unit			
Mode number	Num. eigenfrequency (Hz)	Characte-risation	Num. eigenfrequency (Hz)	Exp. eigenfrequency (Hz)	MAC	Characterisation
1	4.2	Pipe	14.5	14.3		Pipe
2	15.9	Pipe	**18.4**	**18.3**	**0.91**	**1st pump flexion**
3	16.3	Pipe	**21.5**	**21.6**	**0.86**	**2nd pump flexion**
4	19.4	Pipe	23.7	23.5		Pipe
5	23.7	Pipe	29.1	29.1		Pipe
6	24.4	Pipe				
7	25.8	Pipe				
8	27.9	Pipe				
9	31.7	Pipe				

Comparative seismic shearing and tearing reactions at anchorages

On the most loaded anchorages, ratios between equivalent static and dynamical responses, larger than 1.5, can be exhibited on both motor-pump units (Table 2), either using SRSS (Square Root of the Sum of Squares) or Newmark direction combinations. Ratios between equivalent static and time history responses are not systematically larger than ratios between equivalent static and response spectrum responses, especially concerning the vertical flexible motor-pump.

Table 2: Ratios between pseudo-static (PS) and dynamic (response spectrum RS and time history TH) analyses.

		Horizontal pump		Vertical pump	
	Directional combination	PS/RS	PS/TH	PS/RS	PS/TH
Shearing load F_H	SRSS	3.1	3.4	1.6	1.9
Tearing load F_Z		3.7	3.7	4.1	3.7
Shearing load F_H	Newmark	2.7	3.2	2.0	1.9
Tearing load F_Z		2.8	3.0	3.7	3.5

This effect can be related to the fact that the ratio between response spectrum and time history responses can be intrinsically smaller than unity, due to the probabilistic characteristics of the response spectrum method and the small number of time history responses considered (9). Another factor to point out is that the quadratic combination of directional responses is based on their independence, assumption that can be not rigorously respected in case of floor seismic input.

RECOMMANDATIONS

Considering these results, if a finite element model of the pump unit cannot be elaborated, it can be authorized to reduce the 1.5 multi-mode factor for the application of the 1 dof pseudo-static method to the early determination of the loads at anchorages of motor-pump units. Nevertheless, if a finite element model can be available, it is highly recommended to apply the response spectrum method instead of the pseudo-static method. More reliable results and consistency can then be obtained with the response spectrum response of piping.

A first limitation to the general use of this result is related to its example-based validation, even though two different motor-pump units were studied, seismically stiff and flexible. A second limitation is related to the number of time history responses used, nine being a minimal number of responses to authorize confident statistical use.

CONCLUSION

Considering that the earthquake resistance of plant equipments must be verified under increasing seismic levels, methods to determine the seismic loads applied to motor-driven pump anchorages are optimized. The question of reducing the 1.5 multi-mode factor of the 1 dof pseudo-static method is here studied, by comparison with dynamical response spectrum and time history reference results.

On two different motor-driven pump unit examples, seismically flexible with vertical axis and stiff with horizontal axis, the loads at anchorage points are comparatively determined, under actual floor seismic excitations issued from building response to floor seismic loads. It is shown that, based on the shearing and tearing loads on the most loaded anchorages, the pseudo-static method can be reasonably applied using a 1 multi-mode factor. If a finite element model can be elaborated, a dynamical analysis should be however preferably used for more confident and less conservative numerical estimation of motor-driven pump units anchor seismic loads.

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