Comparison of pseudo-static and response spectrum seismic analyses of motor-driven pump units: is 1.5 security coefficient of pseudo-static method relevant?

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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 optimised. 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 opportunity to decrease the multi-mode factor value, by comparison to response spectrum analysis, here considered as the reference method. Comparative seismic analyses are performed on more and more complex dynamical systems and excitations; seismic responses of a thin square plate, motor, pump, motor-driven pump unit connected or not to suction and delivery pipes are thus successively determined, under 1D and 3D excitations. 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 loads at anchorage points.

1 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: optimise the excitation loads and optimise 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 analysis, here considered as the reference method. 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 two seismic equivalent static and response spectrum analyses are presented, with their application on motor-driven pump units. The one-degree-of-freedom pseudo-static method is usually applied to quickly 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.

Comparative seismic analyses are performed on more and more complex dynamical systems and excitations; seismic responses of a thin square plate, motor, pump, motor-driven pump unit connected or not to suction and delivery pipes are thus successively determined, under 1D and 3D excitations. Recommendations are then given about the relevancy of the 1.5 multi-mode factor value for motor-driven pump units.

2 Theoretical backgrounds

2.1 Types of seismic analyses

Seismic analyses used in the design of nuclear safety-related structures are normally conducted using linear, elastic methods. 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.

2.2 The pseudo-static method

2.2.1 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 [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) [2] is applied to take into account the multi-frequency input motion and the multi-modal SSC characteristic, to prevent from possible unfavourable 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 [3]. Number of studies have been performed in order to justify [4][5] or reduce this value.

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 [1]. The method is applicable if its vibrational behavior is not affected by modes, in every principal directions, with eigenfrequency greater than the fundamental one [1]. The method is recommended for systems whose vibrational behavior is not far from a cantilever or clamped-free beam behavior [6].

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 [6];
- 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 [7].

2.2.2 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 Eq. (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.

2.3 The linear elastic response spectrum analysis

2.3.1 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.

2.3.2 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:

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

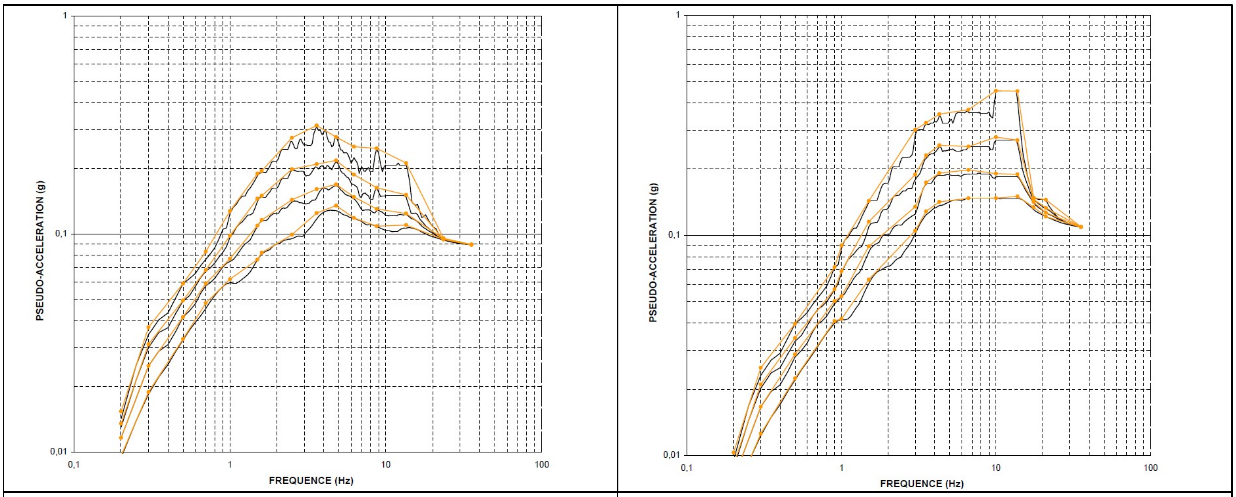
2.4 Comparison methodology

To validate the methodology of equivalent static and response spectrum comparison, more and more complex dynamical systems and excitations are considered. Comparative seismic resulting anchorage reactions are presented within 2 steps: nodal reaction torsor, then shearing and tearing loads. 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.

3 Application to the dynamical pump component and unit models

3.1 Seismic excitation

The spectral accelerations in the three directions are issued from building responses to seismic ground motion, at the floor where the pump units are located. The zero-period acceleration is 35.5 Hz; reduced damping value is 5%.



Horizontal floor spectral acceleration	Vertical floor spectral acceleration

Figure 1: Horizontal and vertical floor spectral accelerations

3.2 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 and Figure 3.

3.2.1 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 6-screw pump locations and 4-screw motor locations for models without frame, or 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).

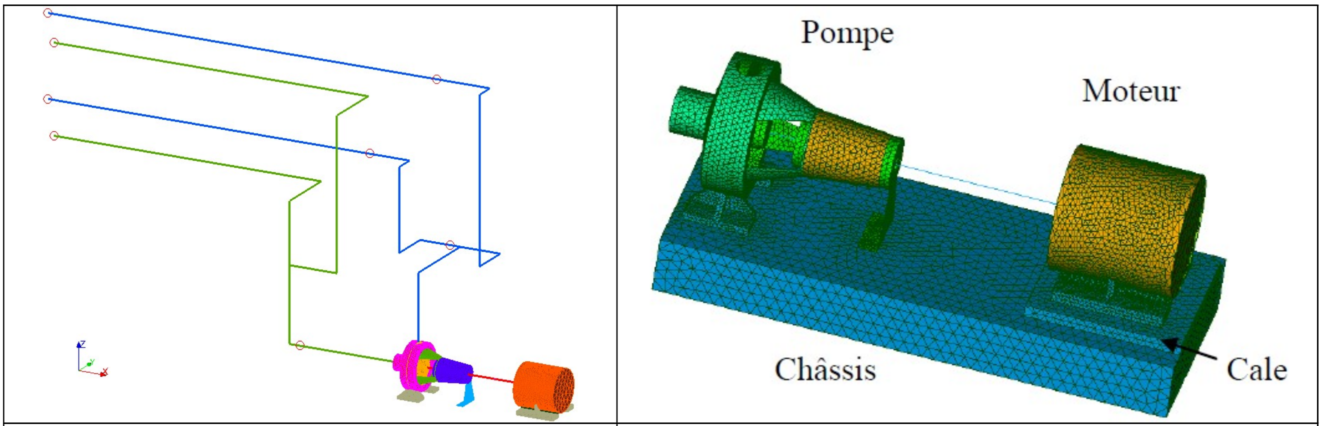


Fig.2.a: Model without frame

Fig.2.b: Motor-pump unit with frame

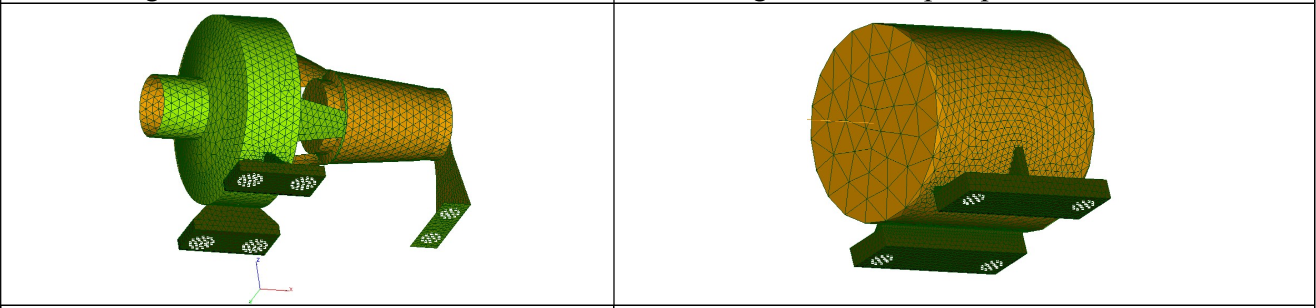


Fig. 2.c: Application discs for screws under pump

Fig. 2.d: Application discs for screws under motor

Figure 2: (a) The horizontal pump unit: model with its pipes (without frame); (b) model with frame (without pipes); (c) pump model; (d) motor model

3.2.2 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.

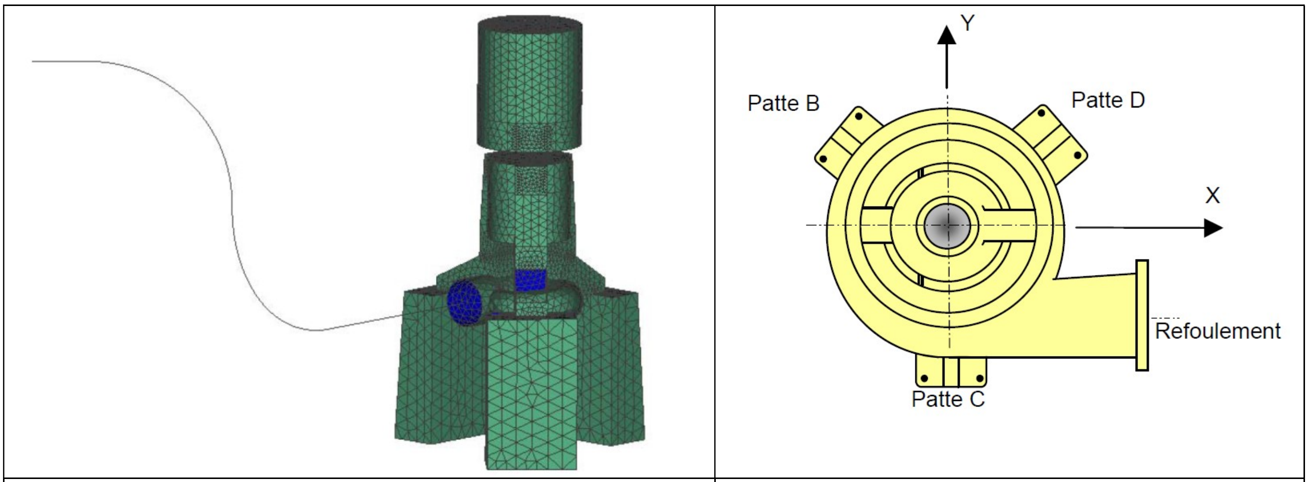


Fig.3.a: The vertical pump unit model and its pipe

Fig.3.b : The three brackets (top view)

Figure 3: The vertical pump unit

3.2.3 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 are present 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.

	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				

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

4 Comparative resulting seismic loads at anchorages

4.1 Horizontal stiff pump unit

4.1.1 Motor

In Table 2 are reported reaction force components and shearing and tearing loads of right back, right front, left back and left front anchorages, issued from response spectrum and pseudo-static analyses, respectively for 1D X-horizontal and 3D seismic excitation. In the right column is summarized the ratio between pseudo-static and response spectrum results, concerning the most loaded anchorage (from pseudo-static results). In case of the 3D-excitation, SRSS quadratic directional combination is applied.

		Response spectrum					Pseudo-static		Ratio
		Right back	Right front	Left back	Left front	Resul-tant		Resul-tant	
1D excitation along Y	F_X (N)	-85.7	98.0	88.2	**-98.5**	0	0	0	0
	F_Y (N)	**-97.8**	-91.0	-97.2	-91.7	-377.7	141	565.5	**1.4**
	F_Z (N)	**-170.0**	-167.1	**170.0**	167.1	0	0	0	0
3D excitation SRSS combination	F_{Htotal} (N)	181.9	**182.1**	182.8	182.3		199.9		**1.1**
	F_{Ztotal} (N)	233.7	225.2	233.6	**224.9**		605		2.6

Table 2: Horizontal stiff pump unit motor
1D horizontal Y-axis: reaction force components
3D excitation: shearing and tearing loads

Due to the motor stiff behavior, it is checked that, for a 1D-excitation, the resulting load issued from the 4 nodal reactions at anchorages, as the response spectrum result in the excitation direction, is equal to the product of the pseudo-acceleration applied (0.21 g) by the motor mass (183 kg), that is 377 N. As it can be theoretically proved, the application of the 1.5 multi-mode factor is not required for the evaluation of this quantity of interest.

The reaction component values are quasi-uniform across the anchorages, that illustrates a relative geometrical motor symmetry.

Orders of magnitude of reaction component values, in the directions orthogonal to the seismic excitation direction and relative to the seismic excitation direction, are the same; for a horizontal along X or Y excitation, vertical reaction component values at anchorages are even greater than the horizontal ones. It can be checked that the resulting 4-anchorage-reaction components is zero, in the directions orthogonal to the excitation direction.

Comparison of resulting shearing and tearing loads shows that taking into account reaction force components, generated in directions orthogonal to the seismic excitation direction, which are calculated by response spectrum method and cannot be considered in pseudo-static method, induces a decrease of the margin observed in 1D excitation results (ratio 1.4 becomes 1.1 for shearing loads, less than 1.5 multi-mode factor).

		Right back		Right front		Left back		Left front	
		Spec. (ESM)	ESM/Spec	Spec. (ESM)	ESM/Spec	Spec. (ESM)	ESM/Spec	Spec. (ESM)	ESM/Spec
3D excitation SRSS combination	F_{Ztotal} (N)	233.7 (383.3)	1.6	225.2 (140.9)	**0.6**	233.6 (604.6)	2.6	224.9 (362.2)	1.6

Table 3: Horizontal stiff pump unit motor
3D excitation: tearing loads
Comparative pseudo-static ESM results at each anchorage

Furthermore, it can be observed that pseudo-static method does not systematically lead to conservative values, if we consider the comparative tearing loads at each anchorage, and not only at the most loaded anchorage. Table 3 shows thus that, under 3D excitation, variability of tearing load values issued from pseudo-static method, relatively to the four anchorages, is high and not coherent with the quasi-symmetry of the motor system; at right front motor anchorage, the pseudo-static tearing load value (140.9 N) is even lower than the reference one (225.2 N), within 0.6 factor.

4.1.2 Motor-pump unit with frame and pipes

Similar comparative analyses are performed on the full motor-pump unit model, including frame and suction and delivery pipes. In Table 4 are reported reaction force components, and shearing and tearing loads of the four application discs for screws, located at the inferior frame face, on right and left sides, under the motor and the pump. These quantities of interest are issued from response spectrum and pseudo-static analyses, respectively for 1D X-horizontal and 3D seismic excitation. Loads resulting from response spectrum analysis are not signed, due to combination of modal responses.

		Response spectrum				Pseudo-static	Ratio
		Motor right	Pump Right	Motor Left	Pump Left		
1D excitation along X	F_X (N)	265.0	**333.4**	265.4	301.1	596	1.8
	F_Y (N)	120.2	71.8	**121.5**	61.7	0	0
	F_Z (N)	**606.5**	339.2	581.1	307.8	0	0
3D excitation SRSS combination	F_{Htotal} (N)	468.4	457.4	**473.9**	470.1	1489	3.1
	F_{Ztotal} (N)	837.0	502.5	**809.5**	563.1	3086	3.8

Table 4: Horizontal stiff motor-pump unit with frame and pipes
1D horizontal X-axis: reaction force components
3D excitation: shearing and tearing loads

It can be shown that shearing and tearing loads determined via pseudo-static analysis overestimate the response spectrum results (3.1 and 3.8 factors respectively) relative to the most loaded anchorage.

4.2 Vertical flexible pump unit

In Table 5 are reported reaction force components, and shearing and tearing loads, determined as the resultant force on the higher stud faces issued for response spectrum evaluation; they are compared with the pseudo-static corresponding results, assuming an equal distribution of the loads on the 3 studs.

F components (kN)		Response spectrum			Pseudo-static	Ratio		
		Bracket B	Bracket C	Bracket D		Bracket B	Bracket C	Bracket D
1D excitation along X	F_X	2.72	1.56	1.84	3.98	1.5	2.5	2.2
	F_Y	1.82	1.93	1.44	0	0	0	0
	F_{Htotal}	3.27	2.48	2.34	3.98	**1.2**	1.6	1.7
	F_Z	7.51	4.60	5.31	0	0	0	0
1D excitation along Z	F_X	0.38	0.45	0.47	0	0	0	0
	F_Y	0.24	0.69	0.28	0	0	0	0
	F_{Htotal}	0.45	0.82	0.47	0	0	0	0
	F_Z	1.01	1.99	1.12	4.63	4.6	2.3	4.1
3D excitation SRSS combination	F_{Htotal}	4.11	4.28	3.51	5.63	**1.4**	**1.3**	1.6
	F_{Ztotal}	8.87	9.05	8.24	33.8	3.5	3.0	4.1

Table 5: Vertical flexible pump unit
1D horizontal X-axis: reaction force components
3D excitation: shearing and tearing loads

Concerning 1D seismic excitation, the 1-dof pseudo-static method overestimates the shearing loads F_{Htotal} with a 1.2 to 1.7 margin, and the shearing loads F_Z with a 2.3 to 4.6 margin, compared with the response spectrum method, depending on the stud considered. Concerning the 3D seismic excitation, the margin varies from 1.3 to 2.1 for the shearing loads and from 2.7 to 4.1 for the tearing loads, depending on the stub considered and the directional combination (quadratic or Newmark).

5 Comments – Conclusion

A series of comparative seismic analyses, based on 1-dof pseudo-static and response spectrum methods, have been performed in order to determine resulting loads at anchorages, on:
- a stiff squared thin plate (not reported here);
- a horizontal seismically stiff motor-pump unit and components;
- a vertical seismically flexible motor-pump unit.

Considering the response spectrum method as the reference method, these quantitative results have permitted to determine the domain of pertinent applicability of 1-dof pseudo-static method, including 1.5 multi-mode factor, for more and more complex excitations and dynamical systems.

5.1 Multi-mode factor nature of 1-dof pseudo-static method

The multi-mode factor has been historically introduced to take into account effects due to multi-frequential excitation and multi-modal dynamical system studied (dynamical cumulative effects possibly defavourable): its 1.5 value is justified on an academic multi-dof example [4]. In case of seismically stiff system, the use of the Equivalent-Static Load Factor is to be evaluated regarding the multi-directional excitation, due to the fact that loads generated in a direction orthogonal to the excitation one cannot be reached by the 1-dof pseudo-static method: the factor is thus proposed to compensate this lack of information.

5.2 Conservatism of the 1 dof pseudo-static method

It has been checked that, for a 1D mono-supported excitation, the resulting load component in that direction, issued from the nodal reactions at anchorages of a flexible multi-modal system, as the response spectrum result in the excitation direction, is less than the product of the pseudo-acceleration applied by the system mass (equal in case of stiff system). As it can be theoretically proved, the application of the 1.5 multi-mode factor is not required for the evaluation of this – and only for this - quantity of interest; in particular, displacement, stress, strain, acceleration quantities are not concerned.

For pump units designed relatively to the most loaded anchorages, the pseudo-static analysis overestimates resulting total shearing and tearing loads. On the studied examples, margin relative to tearing loads is greater than 1.5, but margin relative to shearing loads can be lower than 1.5 (see Table 2, 1D-excitation along horizontal Y axis).

Several effects can be pointed out as an explanation of discrepancies between the two seismic analysis methods:

- assumptions on geometry and dynamical behaviour (§2.2.1) of the motor-driven pump units are not satisfied, for a justified application of the pseudo-static method; representation of this type of equipment by a 1 dof system is not reliable;
- reaction load components induced in directions orthogonal to the seismic excitation direction cannot be obtained using the pseudo-static method.

5.3 Recommendations

Based on comparisons with the reference response spectrum method, if a finite element model of the pump unit cannot be elaborated, it is recommended not to reduce the 1.5 multi-mode factor for the application of the 1 dof pseudo-static method for the early determination of the loads at anchorages.

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.

5.4 Perspectives

Considering the time-history method is more representative than the response spectrum method, further comparisons will be performed between the 1 dof pseudo-static and the reference time-history analyses, in order to possibly reduce the 1.5 multi-mode factor, in case of unavailability of motor-pump unit finite element model.

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