

Dynamic Behaviour of Raft and Pile Foundations Tests and Computational Models: Part 1 — General Description and First Interpretation

J. Betbeder, J.C. Garnier

*Electricité de France, SEPTEN,
Tour EDF-GDF, F-92080 Paris la Défense, Cédex 8, France*

R. Fabries

*Electricité de France, DER,
1 av. du Général de Gaulle, F-92140 Clamart, France*

G.Y. Fenoux

Soletanche Entreprise, 6 rue de Watford, F-92000 Nanterre, France

J. Gauvain

*Commissariat à l'Energie Atomique, C.E.N. Saclay,
Département des Etudes Mécaniques et Thermiques, B.P. No. 2, F-91190 Gif-sur-Yvette, France*

Y. Guillon

Europe Etudes GECTI, 92/98, Bd. Victor Hugo, F-92115 Clichy, France

C. Jeandidier

*Commissariat à l'Energie Atomique,
DSN, B.P. No. 6, F-92260 Fontenay-aux-Roses, France*

C. Plichon

Sofinel, Tour Fiat, F-92084 Paris la Défense, Cédex 16, France

Pile foundations are commonly used for many types of buildings where the bearing capacity of soil is poor. For nuclear power plants buildings, however, there seems to be a fairly general reluctance to accept design on piles, as it is considered difficult to demonstrate the safety of these foundations with respect to earthquakes, due to the relative lack of validation of the currently available aseismic design methods.

Being conscious that pile foundations might be worth considering for future nuclear sites in France and that the reliability of design methods should be backed by experimental data, ELECTRICITE DE FRANCE decided in 1978 to undertake a series of tests, aimed at assessing the validity of computational models for seismic behaviour of pile foundations and trying to define better models if necessary.

These tests on reduced scale structures, including various types of raft and pile foundations and different kinds of dynamic excitation (harmonic, earthquake simulation, impulsive release of a static force) have been made at the NICE airport site. The present paper deals with the general description of the tests and the first part of interpretation work, limited to in-structure harmonic excitation and earthquake simulation tests analyzed by simple spring-dashpot analytical models. The two following papers (K5-6 and K5-7) are devoted to specialized topics in relation with the interpretation of the tests, i-e ground motions analysis for earthquake simulation and research work on a new computational model.

Although preliminary conclusions can be drawn from the results obtained so far, further work will be necessary to reach a conclusive assessment on this difficult subject.

1. Introduction

The behaviour of pile foundations under seismic loading has so far been studied mostly by theoretical means and relevant experimental data are scarce. As a consequence, seismic analysis and design methods for these foundations are still considered by many as insufficiently validated and this is probably why there are presently so few nuclear power plants founded on piles. Even on sites where piles would be well suited to soil conditions, raft foundations are quite often adopted, after the removing or replacement of bad soil, which is an expensive solution.

To investigate the adequacy of computational models and try to derive, if necessary, better models, ELECTRICITE DE FRANCE decided in 1978 to undertake a series of tests. These tests and the results of various types of analyses will be described herein and in the two foregoing papers. The following companies and laboratories participated in preparing, running and interpreting the tests : COMMISSARIAT A L'ENERGIE ATOMIQUE (Département de Sécurité Nucléaire et Département des Etudes Mécaniques et Thermiques), ECOLE CENTRALE de Paris, EUROPE-ETUDES GECTI and SOLETANCHE. The tests themselves ended in april 1979 but analyses are still going on and the material here presented refers to the work done up to february 1981.

2. General presentation of the tests

The main problems encountered in reduced scale seismic tests of foundations are related to :

- similitude conditions for structures,
- earthquake simulation,
- definition of soil properties.

Our main goal being the validation of computational models, we did not attempt to achieve similitude between test models and real structures ; we merely tried to reproduce in the tests some common types of pile foundations, the structures themselves, i-e the part above ground level, being as simple as possible (rigid blocks in fact).

As far as earthquake simulation is concerned, we decided to use the large shock-induced compaction machine which was built for backfill compaction at the NICE airport site ; this machine is capable to drop a 140 000 kg mass from a height of 22 m. It has been shown by preliminary tests that the ground motions induced by the shock of the falling mass have spectral characteristics approximately similar to those recorded from a small magnitude, shallow-focused earthquake ; the acceleration levels are of the order of 0.2 g at 30 m from the impact point. This machine could thus be used as a cheap and reliable earthquake simulator.

Soil properties have been measured by standard tests, such as cross-hole measurements of seismic velocities. As the shock compaction of the backfill has been realized at discrete points, following a square grid pattern with a 14 m mesh size, there is some horizontal heterogeneousness of the soil. The assessment of soil properties for analysis had therefore to take these uncertainties into account.

Four test models have been built ; the part above ground level (a solid concrete cylinder 4 m in diameter and 5 m high), identical for all the models, has an inertia which makes the rocking frequency close to the dominant frequency of the ground motion (6 Hz) ; foundations were different for each model :

- model M1 : raft
- model M2 : 4 concrete piles (0.9 m diameter and 10 m high)
- model M3 : 21 grouted steel piles (0.25 m diameter and 10 m high)
- model M4 : 21 grouted steel piles (0.25 m diameter and 5 m high).

Several types of dynamic tests have been made :

- cross-hole measurements of seismic velocities,
- harmonic excitation of the models ; the excitator was placed at the top of the models ; its force was 6 000 N in vertical and 2 200 N in horizontal.
- earthquake simulation tests by dropping the heavy mass of the compacting machine : various heights of fall were used.
- sudden rupture of a horizontal cable acting on the model with a static force of 2×10^5 N to 6×10^5 N.
- ground vibration tests with a heavy excitator acting on the surface of the ground.

Instrumentation consisted mostly in accelerometers in the soil, on the models and on the piles ; strain-gages were also placed on some of the metallic piles.

The results that are presented in this paper refer to harmonic excitation and earthquake simulation tests.

3. Raft foundation - Harmonic excitation

Harmonic tests have been made before and after the earthquake simulation tests ; it was observed that earthquake simulation tests produced some kind of soil softening, as the measured frequencies under harmonic excitation were lower after these tests.

Experimental results are shown on table 1, where they can be compared to analytical results computed either by soil impedance method or by finite element method. Soil impedance computations assumed the soil to be a homogeneous, elastic half-space, whose characteristics could not be known quite accurately, as mentioned above. Despite this, the agreement between test and computation is reasonably good ; damping values are higher for vertical and horizontal modes than for rocking mode.

TABLE 1

	<u>Experimental results</u>		<u>Analytical results</u>	
	Before earthquake simulation	After earthquake simulation	Soil impedance	Finite element
<u>Vertical mode</u>				
Frequency (Hz)	19.6	18.8	19.9	19.8
Damping (%)	30	37	30	
Velocity on top (mm/s/10 ³ N)	0.09	0.09	0.08	
<u>Rocking mode</u>				
Frequency (Hz)	8.2	7.5	8.5	8.8
Damping (%)	7.3	7.3	7.9	
Velocity on top (mm/s/10 ³ N)	2.35	2.29		
<u>Horizontal mode</u>				
Frequency (Hz)	25-28	25-28	26.5	25.3
Damping (%)	50	50	34	
Velocity on top (mm/s/10 ³ N)	0.13	0.08		

4. Pile foundations - Harmonic excitation

Experimental results are presented on diagrams giving amplitude and phase responses of the models as functions of frequency (Fig.2-3). Response of soil has not been analyzed. The different types of pile foundations produce significant differences in modal characteristics, mainly for damping of the vertical mode and the shape of the first rocking mode.

Simple computer models, similar to those currently in use for design, have been considered and their results compared to tests. These models use the "equivalent unique pile" concept by taking into account the characteristics of each pile and the interaction from pile to pile and from pile to soil.

Such models give computed values which are in fairly good agreement with tests for models M3 and M4 (21 metallic piles) as can be seen from Fig.2-3. For model M2, however, the equivalent unique pile approach seems to fail for vertical response, as it is not possible to define an equivalent pile which gives correct values for both damping and impedance. This method seems to be valid only for a large number of piles, which is usually the case for actual foundations.

5. Raft foundation - Earthquake simulation tests

The strain level in the earthquake simulation tests was 10 to 20 times higher than for harmonic tests. As a result, some non-linear effects have been observed ; Fig. 4 shows for instance the decrease of frequency and the increase in damping on the transfer function between free-field and model M1 motions, when the motion amplitude is increased.

To take into account this non-linearity, a relation between shear modulus and strain level has been derived as follows : a static, axisymmetric finite element model has been made for the soil including its various layers ; a mean strain has been defined by averaging strains in the different layers on a total depth equal to two times the diameter of the raft ; the relationship between horizontal acceleration on top of the model and mean strain γ_m has thus been established. By plotting the square of the ratio between observed and initial frequency as a function of strain level, an approximation for the curve $G/G_{\max} = f(\gamma_m)$ has been obtained ; this curve, shown on Fig. 5 , can be compared to standard results for sands. The same figure also shows the relation between damping and strain.

The response measured on the model has been compared to the results obtained by computation ; stiffness of soil springs has been derived from the FOURIER transform of the impulsive step response of the structure, using a finite element model for the layered soil and shear moduli values estimated from the curve of Fig. 5 for the expected level of motion. The response of the structure has been computed from free-field ground spectra in the horizontal and vertical direction, using quadratic combination for the effects of the two earthquake components. Comparison with experimental values (Fig. 6) can be described as fairly good, computed results being slightly conservative.

6. Pile foundations - Earthquake simulation tests

As for the raft model, a non-linear behaviour can be observed on experimental results showing that fundamental frequency and damping depend on the amplitude of motion, which is a function of the height of fall of the mass. This dependency is shown on Fig. 7 , where points corresponding to low-amplitude motions (harmonic tests) have also been plotted.

It should be noted that the recorded response of the models shows a significant transverse component of motion (i.e at right angle to the path from impact point to model). This fact demonstrates clearly the heterogeneous character of the soil.

Computations have been carried out with the same types of models than those which had been used for harmonic tests (see Fig. 8). Comparisons with experimental results have been disappointing the main reason for this being, presumably, that these models are made for the usual assumption of vertically propagating shear waves, which is not well suited to the type of ground motions generated during the tests. Although the same difficulty exists when computing the response of the raft model, the depth of pile foundations apparently makes the influence of the seismic wave model much more critical.

7. Conclusions

As mentioned previously, the results which have been presented are to be considered as preliminary and further analysis will be required to ascertain our first conclusions and give interpretation for the whole series of tests. From the present state of our studies, one can draw the following conclusions :

- 1 - Such tests made with real soils require considerable care in analyzing the soil data and selecting the most appropriate ways to measure mechanical characteristics and response of soil and structures.
- 2 - As pile foundations are needed for bad soils, whose behaviour is far from the usual elastic assumption, it is essential to take into account the non-linear effects.
- 3 - The uncertainties in assessing soil properties have to be reckoned with and should be accounted for in the design methods, whatever they are.
- 4 - The usual impedance method for raft foundations seems to be reasonably accurate, even in cases when the vertically propagating shear wave assumption is not perfectly met.
- 5 - Simple analytical models for pile foundations, based on spring assumptions for the various interactions between piles and soil, seem to work reasonably well, provided that the number of piles is large enough and that the dynamic loading is simple, as it was the case for the harmonic tests.
- 6 - The same models may be adequate for earthquake loading in case of vertically propagating shear waves, but this conclusion should be substantiated by further work.

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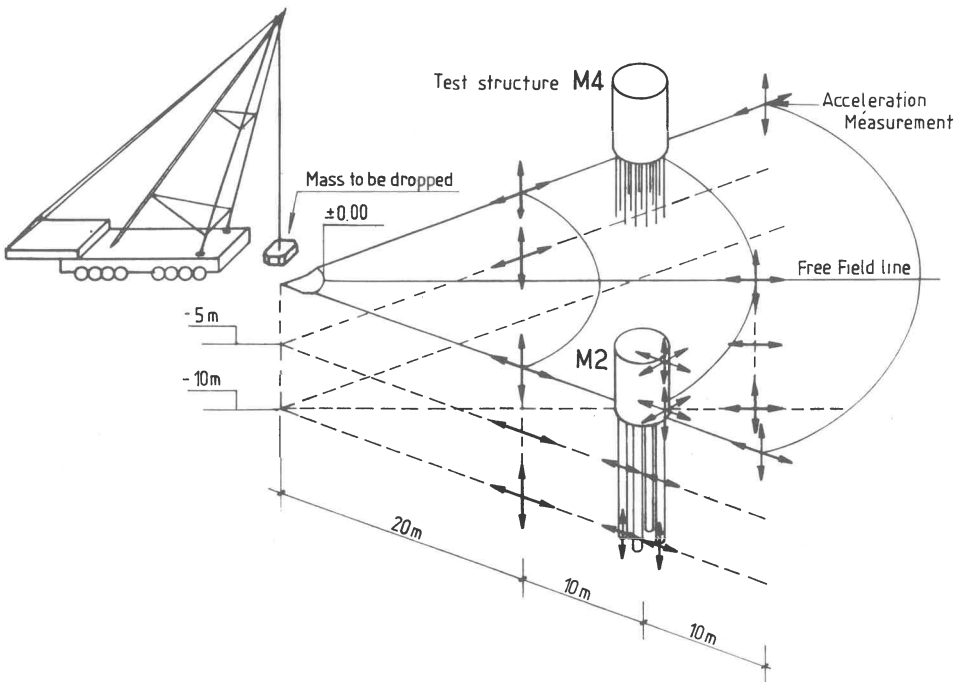
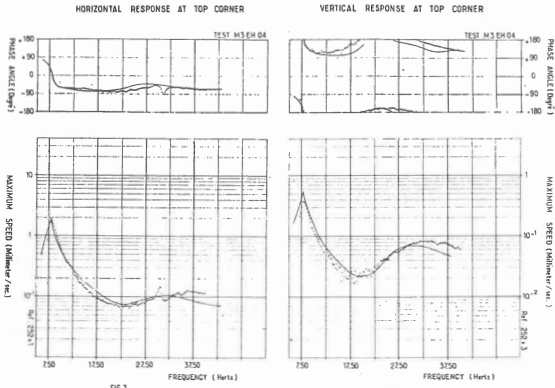


FIG.1 SCHEMATIC TEST INSTALLATION



COMPARISON BETWEEN COMPUTED (continuous line) AND MEASURED (little crosses) RESPONSE OF STRUCTURE M3 (21 long piles) UNDER HORIZONTAL HARMONIC EXCITATION AT TOP (scaled to 1000 Newton)

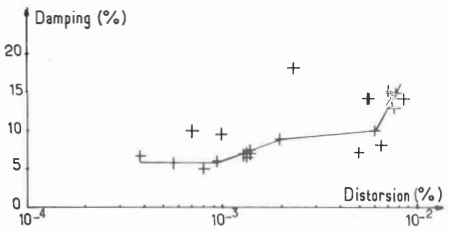
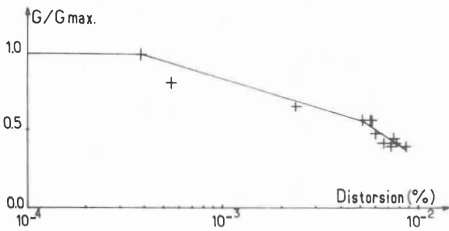


FIG. 5

SOIL IMPEDANCE PARAMETERS RELATED TO COMPUTED DISTORSION (test structure M1)

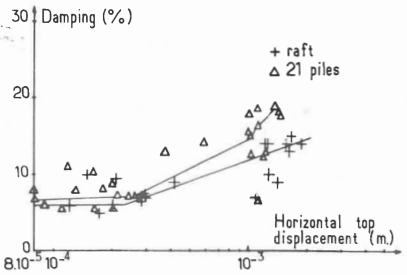
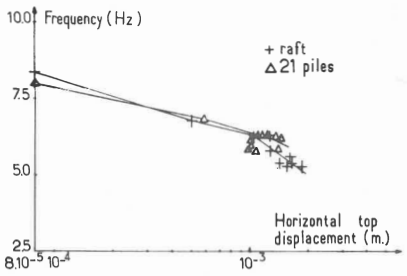


FIG. 4

EFFECT OF AMPLITUDE ON MAIN RESPONSE PARAMETERS (Measured values for test structure M1 and M3)

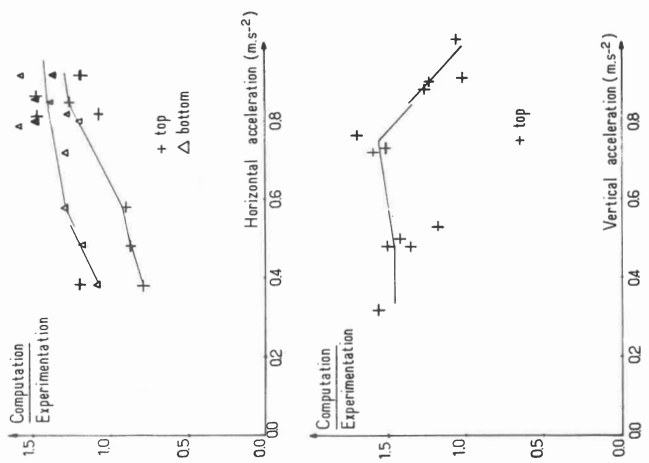


Fig. 6
CHECK OF COMPUTED RESPONSE
(Test structure M1)

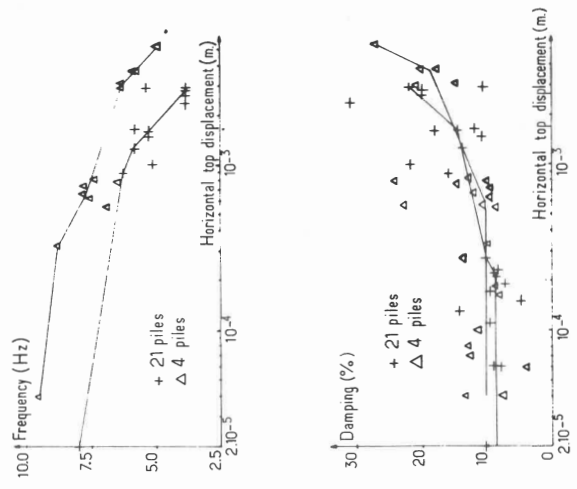


Fig. 7
EFFECT OF AMPLITUDE ON MAIN RESPONSE PARAMETERS
(Measured values for test structure M2 and M4)

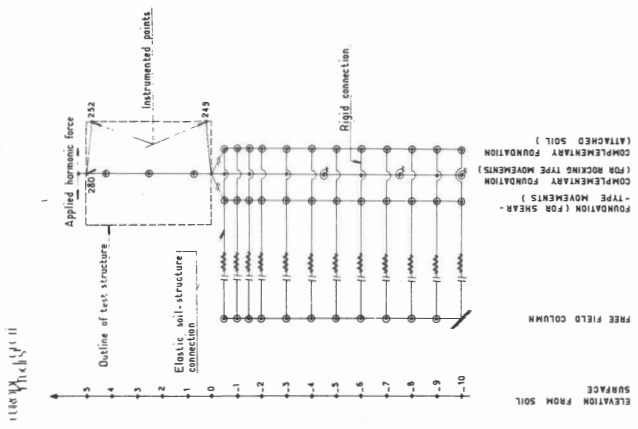


Fig. 8
SCHEMATIC REPRESENTATION OF MODEL USED FOR
TEST STRUCTURE M3