DEVELOPMENT AND APPLICATION OF A PROCEDURE FOR SEISMIC DESIGN OF OFFSHORE PLATFORMS

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SUMMARY

A procedure for seismic design of offshore platforms is described and illustrated by example. Site-specific response spectra, evaluation of soil stability, and other geotechnical input for structural analysis are generated by nonlinear site response and soil-pile interaction programs SRANG and NONSPS. Structural analysis is conducted by any of several linear elastic programs available to the offshore industry. Results of analysis of a drilling platform controlled by earthquake loading are reported. The procedure is both simple and economical to use, making it feasible to include sensitivity and parametric studies as a routine part of seismic analysis.

INTRODUCTION

The paper presents an economical and rational design procedure developed for earthquake analysis of pile and jacket founded offshore structures. In recognition of a general need in the offshore industry for an economical and user-oriented procedure for seismic design, the following basic guidelines were adopted to govern the development:

- Interface between structure and foundation is the pile head. A soil-pile-structure interaction model provides the pile head response values needed for structural design.
- This model incorporates state-of-the-art representation of soil-pile-structure interaction during earthquake shaking, and uses a lumped-mass, single-pile representation of the structure.
- Structural analysis is by linear computer programs such as STRAN, SACS, and STRUDL as these programs are available to offshore engineers worldwide.

In the foundation model, complex nonlinear soil-pile interaction effects are evaluated to provide the following information for structural design: shear at each level of the platform; values for the pile head stiffness matrix; response spectra for pile head acceleration; maximum pile head acceleration; and system energy absorption.

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The procedure has unrestricted application for strength level design since offshore codes require elastic structural behavior during strength level (API) or design level (DnV) shaking. In addition, there are many sites for which structural member and joint behavior remain practically linear and elastic throughout earthquake shaking intense enough to develop four or more times the system energy occurring at "strength" level (API "ductility" level), and two or more times the lateral displacements occurring at "design" level (DnV "exceptional" level). In these cases, also, the designer is able to use linear analysis to satisfy code requirements.

An example illustrates a typical combination of site conditions, platform structure and topside mass to which the procedure applies for exceptional as well as strength level shaking.

BACKGROUND DISCUSSION

Various methods have been developed in recent years to evaluate the soil-pile-structure interaction. Two typical approaches are shown in Fig. 1. The approach (a) employs an entire structure including the soil-pile system. Although the method can reproduce three-dimensional responses of the platform, it can be prohibitively expensive when the platform responses are computed with nonlinear soil supports. Thus, this type of analysis is economically feasible at present only when the effects of nonlinear soil supports are approximated by linear springs.

Some numerical studies (Refs. 1, 2, 3, 4) and experience with earthquake damage to pile foundations (Ref. 5) have shown that the response of a pile structure can be affected significantly by the performance of foundation soils. In the approach (b), the major emphasis is on the detailed modeling of the soil behavior. The method, however, is comparatively economical as complex, nonlinear soil behavior is evaluated in a simple model, and the method is suited particularly to parametric studies to quantify the sensitivity of platform-pile response to the variations of major input parameters.

The design procedure described here is based on this concept, and involves the following major steps:

(1) Three-dimensional static analysis of the platform to determine the masses and stiffness for the lumped-mass structural model.

(2) Three-dimensional dynamic analysis of the soil-pile system to establish a single-pile model.

(3) Analysis of a single-pile system with detailed foundation soil characteristics and an idealized lumped-mass structural model.

(4) Detailed structural response analysis using the results from the third step.

Detailed descriptions of all tasks involved are presented in the next section. Steps (1) and (4) are accomplished by using a standard linear structural analysis program, and Step (2) is accomplished by a numerical method for dynamic pile-soil-pile interaction, PILES (Ref. 6).

The single-pile analysis in Step (3) is made by the NONSPS (NONlinear Soil-Pile-Structure) program (Ref. 3). The program is based on the beam-on-Winkler foundation model of Fig. 2. An important feature of the program is that it incorporates rational soil-pile interaction elements and reproduces realistic soil-pile responses (Refs. 3, 7).

ANALYSIS PROCEDURE

The initial three-dimensional structural model for seismic analysis (Fig. 3) is usually the result of design for wave loading. Members and joints have been sized and results of a coupled soil-pile-structure interaction analysis are available. Input data required for the NONSPS model of Fig. 2 may now be prepared.

Quantities required are rotational restraint at the pile head provided by structure above; overturning or rocking stiffness of the entire platform; flexural stiffness of the platform above the pile heads; and allocation of mass to each level. Pile head restraint and overturning stiffness are obtained from the static wave load analysis by elementary methods. Sensitivity studies show that a refined calculation of these quantities is unnecessary, as is illustrated in the following example. See Table 1.

Flexibility of the platform is computed by fixing supports at the pile heads and applying unit horizontal loading successively at each level. The resulting flexibility matrix contains the stiffness information required. Platform and live load masses, including added mass of submerged members, are lumped at each level by tributary procedure.

Seismic analysis by the single-pile model of NONSPS provides the four quantities shown in Fig. 3. Pile head springs refer to elements of the six-by-six stiffness matrix of the pile head. These quantities permit completion of the three-dimensional structural model for dynamic analysis. Energy is computed for the entire soil-pile-structure system and is used to define free-field accelerations for design earthquakes of intensity higher than the basic event. Providing system energy information at this early stage of seismic design is a particularly useful feature of the NONSPS model. More commonly, energy computations come later from the three-dimensional model where it is difficult to account for the contribution of nonlinear pile and near field soil interaction.

Two other important results are the evaluation of soil stability and the distribution of global horizontal shear. By the recommendations of API RP 2A (Ref. 8) full earthquake design provisions apply for Zones 1 and 2 only if the seismic shears exceed one-half those from wave loading. Thus, it is possible at this early stage to evaluate the basic structural framing and make revisions before proceeding with response analysis of the full structural model.

Response analyses and platform detailed design are accomplished using a suitable suite of linear structural analysis programs. Several general treatments of the theory and techniques used in these programs are available. See Ref. 9 for example.

EXAMPLE ANALYSIS

Fig. 4 gives the principal features of an offshore platform analyzed by this procedure. Soil conditions are 20 meters of very soft to stiff clay overlaying a deep layer of hard to very hard clay. Strength level free field shaking was set at 0.09g (API Zone 2). The topside mass is representative for platforms supporting two drilling rigs. Jacket members and piles were sized for wave loading using the criteria of Ref. 8. All input data required for the NONSPS model are shown.

Output from NONSPS analysis is given in Figs. 5, 6, 7, and 8. Seismically-induced shear at each platform level was computed and found to be slightly greater than wave load shear. Thus, full earthquake design provisions of Ref. 8 were considered applicable. Only minor structural changes were required as a result of the response analysis. These consisted of increasing the diameters of a few diagonal braces and some horizontal members at the top level of the jacket to improve stability. This was done without significant effect on either weight or dynamic response.

Figs. 9 and 10 show response for three of the more highly loaded members. Stresses were computed by the SACS suite of programs (Structural Analysis Computer System, Engineering Dynamics, Inc., U.S.A.). Values are for gravity loads combined with seismic response loads. Modal analysis was used and responses of the individual modes were combined by root-sum-square (RSS) procedure. Yield strength for jacket members is 250 MPa, and for piles, 345 Mpa. The results show that stresses are below yield at the ductility level shaking defined in Ref. 8 (four times strength level energy criterion). Even at free field intensity causing system energy twelve times that of strength level the most critical member, a deck leg, was stressed only slightly above yield, and maximum pile stress was just at yield. Piles checked by the overload criterion of Ref. 8 were found to be at about 60% capacity. Horizontal deflection at the top of the platform is plotted in Fig. 11. There was practically no difference in deflection for the two cases of full and one-half topside mass.

CLOSING REMARKS

Application of this procedure for seismic analysis of platforms in water depths to 130 meters subjected to shaking intensities to 0.2g has shown that the development objectives were achieved. One of the most essential results is the evaluation of soil stability at the platform site, particularly when potential for liquefaction is high. Early access to system energy and platform level shears has been particularly useful for selecting jacket framing in cases borderline between wave or earthquake critical structures. Also, it has been demonstrated that parameter sensitivity studies such as shown in Table 1 can be conducted conveniently and economically, and easily made a routine part of the analysis. On occasions where controlled comparisons were made of global base shear and moment and pile head shear and moment, computed by both NONSPS and the three-dimensional structural model, agreement within 10% was achieved.

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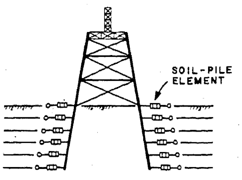
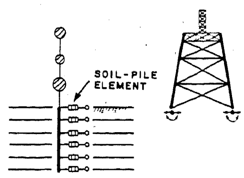
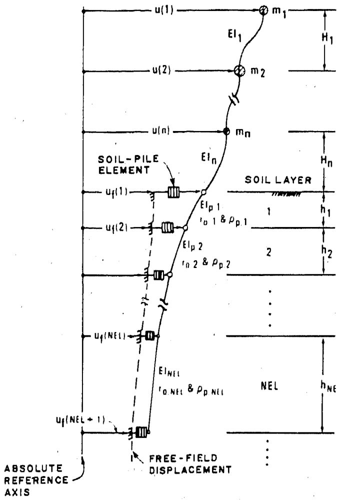


(A) ENTIRE STRUCTURAL ANALYSIS



(B) STRUCTURAL ANALYSIS

FIG.1 GENERAL PROCEDURES
FOR PLATFORM RESPONSE ANALYSIS



NOTE:

TWO SPRINGS ARE PROVIDED AT THE BASE OF THE STRUCTURE. ONE SPRING REPRESENTS THE ROCKING STIFFNESS OF THE STRUCTURE. ANOTHER SPRING IS USED TO INCLUDE THE ROTATIONAL CONSTRAINT AT THE PILE-JACKET CONNECTION.

FIG. 2 ANALYTIC MODEL FOR PROGRAM NONSPS

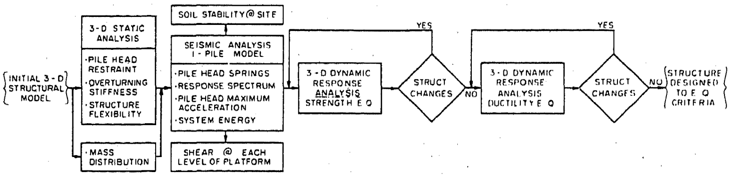
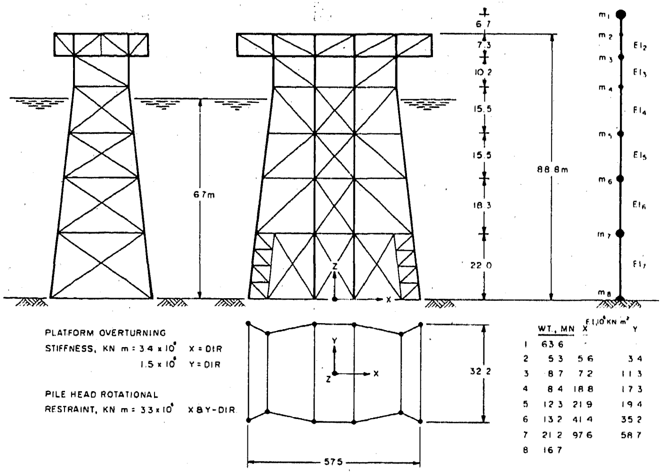


FIG. 3 ACTIVITY NETWORK FOR PLATFORM DESIGN



PLATFORM OVERTURNING
STIFFNESS, KN m = 3.4 x 10⁸ X = DIR
1.5 x 10⁸ Y = DIR

PILE HEAD ROTATIONAL
RESTRAINT, KN m = 3.3 x 10⁶ X & Y-DIR

	WT., MN	EI,10⁸ KN m² X	Y
1	63.6		
2	5.3	5.6	3.4
3	8.7	7.2	11.3
4	8.4	18.8	17.3
5	12.3	21.9	19.4
6	13.2	41.4	35.2
7	21.2	97.6	58.7
8	16.7		

FIG.4 LUMPED MASS MODEL OF PLATFORM

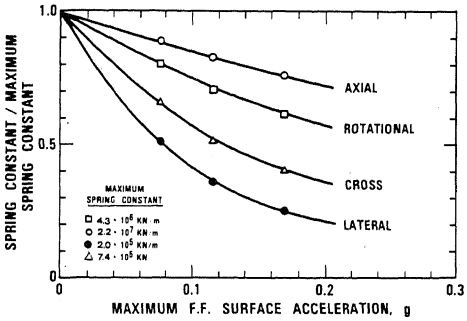


FIG. 5 VARIATION OF PILE-HEAD SPRING CONSTANTS WITH EXCITATION LEVEL

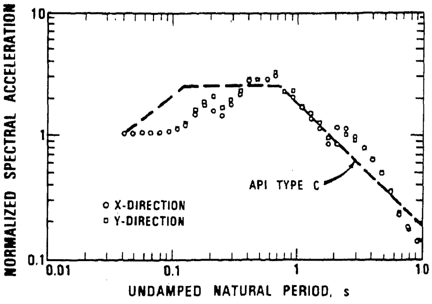


FIG. 6 RESPONSE SPECTRA AT FIXED BASE

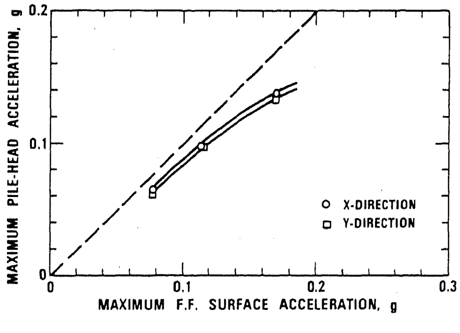


FIG. 7 MAXIMUM PILE-HEAD ACCELERATIONS

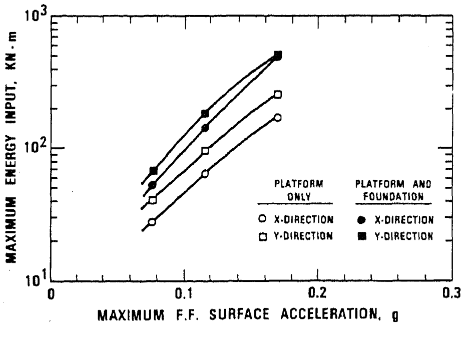


FIG. 8 VARIATION OF SYSTEM ENERGY WITH EXCITATION LEVEL

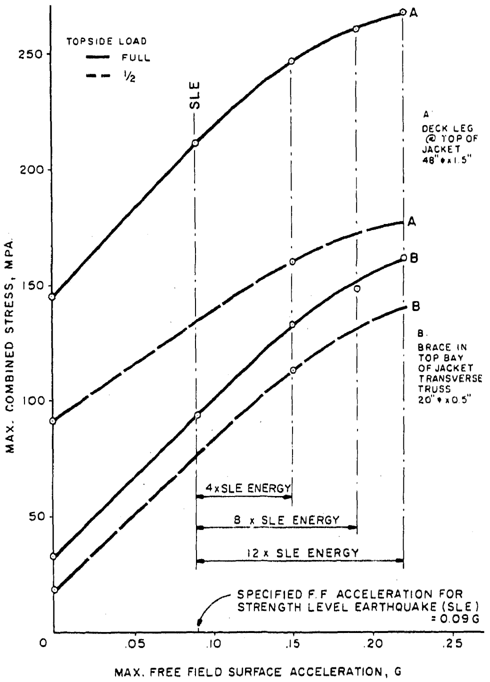


FIG. 9 DECK LEG AND JACKET BRACE STRESS

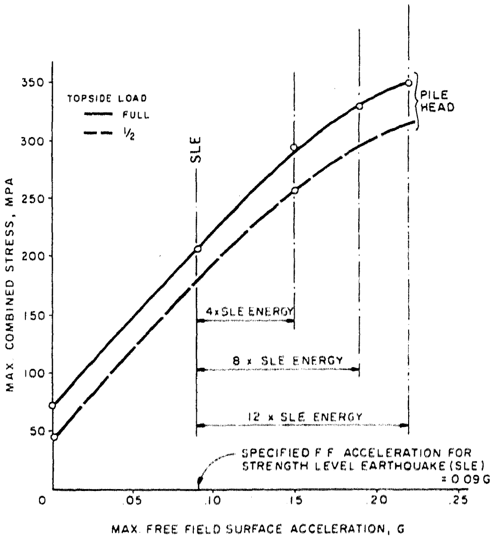


FIG. 10 PILE HEAD STRESS

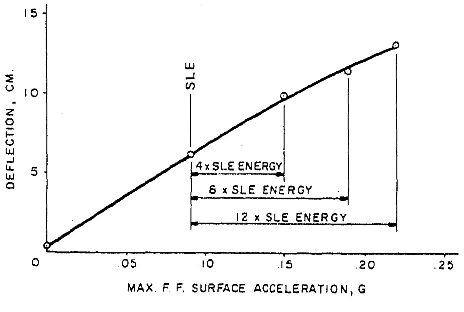


FIG. 11 TRANSVERSE DEFLECTION @ MAIN DECK

TABLE I

EFFECTS OF VARIATIONS OF STRUCTURAL PARAMETERS AND SOIL STRENGTH

	(1)	(2)	(3)	COMBINED
BASE SHEAR	1 %	3 %	4 %	8 %
OVERTURNING MOMENT	2	3	2	7
PILE SHEAR	2	6	20	30
PILE MOMENT	5	3	22	32

(1) VARIATIONS IN RESPONSES DUE TO +/-42 % CHANGE IN THE ROTATIONAL STIFFNESS OF THE PILE-TO-JACKET JOINT.

(2) VARIATIONS IN RESPONSES DUE TO +/-33 % CHANGE IN THE ROCKING STIFFNESS OF THE PLATFORM.

(3) VARIATIONS IN RESPONSES DUE TO +/-50 % CHANGE IN THE UNDRAINED STRENGTH OF SOILS.