Geologie en Mijnbouw **73:** 303–307, 1994.

Loading of foundation piles during the 1992 Roermond earthquake, the Netherlands

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Received 14 June 1993; accepted in revised form 7 January 1994

Key words: interaction, dynamic loading, bored piles

Abstract

In order to assess the influence of the 1992 Roermond earthquake on a piled foundation, a pile and the interacting mass of the supported structure were modelled. The model represents a typical pile in the Maasniel area of Roermond, the Netherlands. Results indicate that piles are subjected to significant loading. Popular belief that wind-loading conditions in the Netherlands impose higher loads on the foundation piles than an earthquake like the one in Roermond is not correct. Especially bored (in-situ fabricated) pile types may be loaded beyond their elastic range. Recommendations for verification and improvement of the model are given.

Introduction

The effects of the April 13, 1992 earthquake on foundations were investigated at the request of the Municipality of Roermond. Although the study focused on the Maasniel quarter in Roermond the results are believed to have a more general applicability.

Steps of the study relevant to this paper consisted of:

- a geological and geotechnical study to determine a representative soil profile and corresponding dynamic soil parameters,
- assessment of the earthquake intensity,
- selection of an appropriate soil response spectrum,
- generation of a synthetic acceleration record in horizontal direction,
- determination of horizontal soil movements at depth, corresponding with the synthetic acceleration record,
- modelling a typical foundation pile in the Maasniel area and subjecting this pile to the aforementioned soil movements.

A brief description of the first steps is given below. Detailed information can be found in the companion paper Meijers et al. (1994). In the present paper the pile model and the results obtained from that model will be discussed in more detail.

Determination of representative soil movement

On the basis of an assessment of the resulting structural damage and a back-calculation of some of the observed failure mechanisms the earthquake epicentral intensity was estimated to fall in class VII, both on the MM and the MSK scales. At the time of this study (autumn 1992) a best estimate of the peak ground acceleration was put at 0.9 m/s^2. On the basis of this information and the local geology a ground response spectrum was selected from the publication of Hosser (1987). From the same source the variation of the average acceleration amplitude with time during the earthquake was taken. A synthetic ground surface acceleration record for lateral movement was (iteratively) generated in such a way that it complied with the earthquake characteristics described here. The end-velocity following from the generated record was set to zero by adding a small acceleration correction term of zero frequency. No attempt was made to affect the end-displacement following from the generated record, as pile loads proved to be completely dominated by the soil acceleration and not the soil displacement.

From this synthetic record a corresponding set of soil acceleration records at various depths below the ground surface was derived, using the computer code SHAKE (Schnabel et al. 1972). Finally, for use in

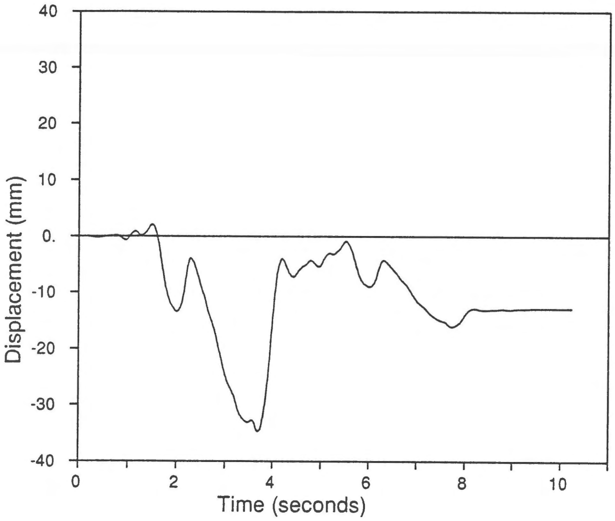

Fig. 1. Synthetic horizontal displacement record for soil movement at the surface. This displacement is comparable with the one that occurred during the 1992 Roermond earthquake.

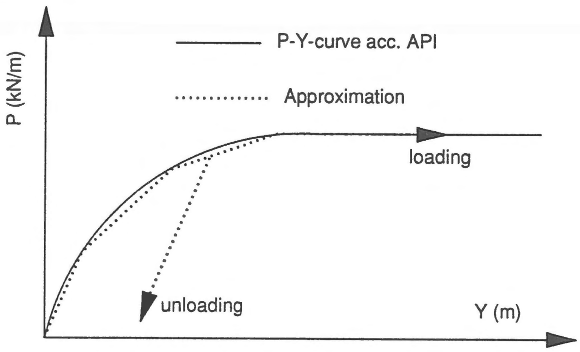

Fig. 2. The relation between soil reaction force (P) and lateral pile displacement (Y) or the so-called P-Y curve (solid line) and an approximation (broken line) of this curve.

the pile model the acceleration records were integrated twice, in order to obtain time-displacement records at all depths where input for the dynamic pile model was required. As the main components of the generated earthquake record have relatively long wavelengths (compared to the length of a foundation pile) lateral soil movements along the pile are almost completely in phase. Therefore, the soil movement record at the surface gives a good approximation of the loading which was used in the pile-structure calculations. This synthetic record is shown in Fig. 1.

The model

The computer program TILLY, developed by Delft University of Technology (TILLY R & D Group 1992), was used to model a foundation pile. The program TILLY is an implementation of a so-called discrete element method (Blaauwendraad 1989). In this method the investigated model is composed of a collection of masses, elastic and elasto-plastic springs, and dashpots. Masses are associated with parts of the structure which have a degree of freedom (the possibility to move). Appropriate masses are assigned to discrete parts of the pile and the structure above. Links between the various degrees of freedom are defined by means of kinematic relations which describe the deformation of specific elastic or elasto-plastic springs.

Pile characteristics and model

For the analysis a bored concrete pile was selected. The pile has a length of 11 m and a diameter of 0.3 m. The pile itself is modelled as an elastic beam. Possible nonlinear behaviour of the pile is not accounted for. The model consists of a sequence of 11 rigid elements with appropriate mass, connected by means of rotation springs.

Pile-soil connection: P-Y curves

The relation between lateral pile displacement and soil reaction force (P-Y curve) is taken in accordance with the recommendations of the American Petroleum Institute (API 1989). The initial stiffness is determined on the basis of the relative density of the soil and the local depth below ground surface. A reduction factor accounts for the degrading effect which is the result of the cyclic loading. The curved relation is approximated by four linear pieces as shown in Fig. 2, being the force-displacement relation of three parallel elasto-plastic spring elements. To account for the geometric (radiation) damping and increased stiffness under dynamic loading conditions, a dashpot is added parallel to the aforementioned elasto-plastic springs. The damping is set at 15 percent per period.

Superstructure and pile connection

The superstructure is modelled as a concentrated mass at the pile head. Because of the axial stiffness of adja-

Table 1. Input data and results for discrete element modelling of dynamic loading of bored piles. Seven different pile characteristics have been considered

Calc. No.	E concrete (GPa)	Mass (kg)	Maximum pile head acceleration (m/s^2)	Maximum bending moment (kNm)	Maximum lateral loading (kN)
1	40	70 000	2.03	77.3	142
2	40	35 000	1.88	35.4	66
3	40	17 500	1.89	16.0	33
4	20	70 000	2.01	69.9	141
5	20	35 000	1.76	26.6	62
6	20	17 500	2.40	17.5	42
7 (*)	40	70 000	1.40	78.4	98

(*) Note: Calculation 7 has pinned pile head condition. E: modulus of elasticity.

cent piles in the prototype situation, horizontal translation movement of the structure is dominant. Hence rotation movement is excluded from the model. For most calculations it was assumed that the pile had a fixed connection to the structure, implying that rotation at the pile head is prevented. One comparative calculation (no 7) was made with a pinned (hinged) connection between pile and structure.

Calculations

A total of seven calculations has been performed (Table 1). The initial situation is a system at rest. For the soil next to each pile node individual lateral displacements, varying with time, are imposed in accordance with the result from the SHAKE calculations. For the mass of the superstructure values of 70 000, 35 000 and 17 500 kg have been taken. The modulus of elasticity (E) of the concrete pile has been varied between 20 000 and 40 000 MPa. The design load of the piles is in the order of 30 MN.

Results

In order to illustrate the type of movement which follows from these calculations the lateral pile head displacement and lateral soil displacement for calculation no 7 are plotted in Fig. 3. It can be seen that the large mass and relatively small damping lead to a slowly decaying vibration of the structure. In Table 1 the key input data and main results are presented for all calculations.

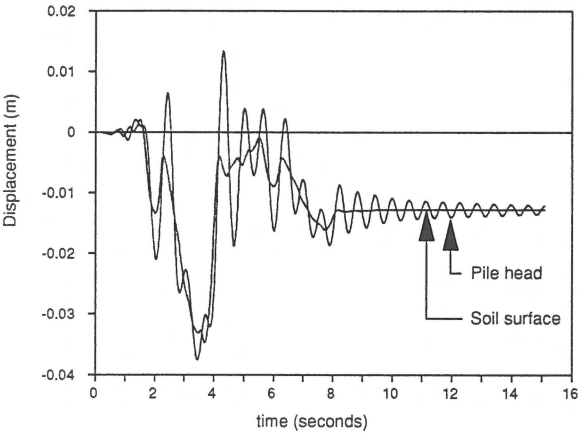

Fig. 3. Horizontal pile-head and soil-surface displacements for a hinged pile (calculation 7 in Table 1).

The fixity of the pile head in the structure had (in this case) no influence on the maximum bending moment. The main difference between results of calculation 1 and 7 is the shift of the location where the maximum bending moment occurs: for the fixed pile (calculation no 1) at the pile head, and for the pinned pile (calculation no 7) approximately 2 m below the pile head.

Table 2. Tension crack threshold and vertical load eccentricity for the seven models specified in Table 1

Calc. No.	Bending moment at first yield (kNm)	Required eccentricity (m)
1	23.3	0.125
2	11.7	0.115
3	5.8	0.103
4	23.3	0.113
5	11.7	0.086
6	5.8	0.113
7 (*)	23.3	0.127

Interpretation

In Table 2 the bending moment associated with first yield (horizontal tension cracks at the edge of the pile) and the corresponding eccentricity of the vertical load are given for seven calculations. The vertical load which is exerted by the superstructure has in this case a beneficial effect on the maximum allowable bending moment. During the earthquake this vertical load (9.81 times the masses quoted in Table 1) will vary as a result of the vertical ground accelerations.

For the interpretation of the allowable bending moments it has been assumed that:

- no reinforcement is present (bored piles have generally very limited reinforcement),
- the minimum effective vertical load during the earthquake is 0.9 times the static vertical pile load,
- this minimum occurs simultaneously with the maximum bending load.

Not surprisingly, the maximum horizontal load on the pile, corresponding to the maximum horizontal acceleration of the superstructure, conforms quite well with the ground-response spectrum which forms the basis for the synthetic record (Meijers et al. 1994). Since the ground response spectrum predicts a 2 m/s^2 acceleration for systems with eigenfrequencies between 1.5 and 5 Hz, no large influence of soil properties is found and the calculation results are applicable to other soil and foundation types as long as the pile-structure eigenfrequencies fall in the same range. The peak structure accelerations create horizontal loadings which are in the order of 20% of the static vertical load.

Except for very high and exposed structures wind load magnitudes less than 10% of the weight of the structure are quite common. If follows therefore that the maximum seismic loads could exceed the wind loads by a factor two.

Conclusions and recommendations

On the basis of the above calculations it is expected that in bored piles without significant reinforcement or prestressing horizontal tension cracks develop. The pile is able to withstand loads exceeding the level where tension cracks develop, as long as the vertical load (normal force) can shift its line of work.

The maximum shift (maximum eccentricity) depends on the vertical load on the pile and the quality of the concrete of which the pile is made, as compressive overloading may develop at the edge of the pile.

A horizontal tension crack is expected to have a minor influence on the future behaviour of the pile, both during lateral and/or axial loading, as the static load will guarantee compressive prestressing and shear stress transfer capacity of eventual cracks.

Development of a (partial) plastic hinge due to tension cracks on one side or exceedance of the compressive strength on the other side of the pile will affect the moment distribution in the pile. This will cause a location shift and possibly a decrease of the maximum bending moment. The dynamic shear force (lateral/horizontal load) will have a detrimental effect on the allowable bending moment. The maximum shear force occurs simultaneously with the maximum bending moment.

Improvements of the above calculation method can be achieved by accounting for:

- nonlinear (plastic) behaviour of the pile,
- position of the mass of the superstructure at a more realistic (higher) level above the pile head,
- swaying motion of the structure, which leads to larger variations in the vertical pile load,
- vertical seismic ground movement as extra input load.

On the basis of this type of calculations the earthquake loading level of piles of different diameters and with different superstructure masses may be determined. For the Maasniel situation it is found that bored piles with diameters of 0.3, 0.4 and 0.5 m and superstructure masses of 37 500, 80 000 and 145 000 kg, respectively, lie at the boundary of the 'critical' range. It is concluded that the earthquake has imposed heavy loading on bored foundation piles. However, so far there is no proof that critical overloading has occurred in the field.

It is therefore recommended that, in cases of re-use or extra loading of existing pile foundations, the integrity of the piles is verified by means of a physical inspection of the piles if they exceeded the aforementioned critical range at the time of the earthquake.

Acknowledgement

The authors gratefully acknowledge the contribution of the Municipality of Roermond, which commissioned the study that formed the basis for this paper.

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