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Dynamic vibro-structure-soil interaction mechanism of vibrodriven sheet piles -a simplified view

Mécanisme dynamique d'interaction vibro-structure-sol de palplanches vibrant -une vue simplifiée

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ABSTRACT: This paper presents results of documented soil motions in the ground based on full scale field tests of vibro-driven sheet piles. A novel simplified analytical view of the transfer mechanisms is presented for singular and in interlock driven sheet piles, describing the dynamic vibro-pile-soil-interaction at shaft as well at pile toe. The view comes out of experiences from numerous conducted field tests, based on a range of different results from self-developed sensors that's been mounted; on the driven piles, left in place on preinstalled piles, on- and in-depth of the soil at different radial distances in the soil volume beside the driven pile. The vibration transfer to soil at the pile-soil interface boils down to the pile motion. The motion of the pile is a consequence of how the driving force enters the driven profile. Results of infield observed soil motion are presented, the effects of how the pile vibrates both vertically, horizontally as well as transversally and how the motion of the driven profile connected to the adjoining sheet pile wall, is set into motion as well and therefore also transfers vibrations into the nearby soil.

RÉSUMÉ: Cet article présente les résultats du mouvement documenté du sol dans le sol, sur la base d'essais sur le terrain à grande échelle de palplanches pilotées par vibrations. Une nouvelle vue analytique simplifiée des mécanismes de transfert est présentée pour les palplanches singulières et les serrures couplées, décrivant l'interaction dynamique pile-sol au niveau de l'arbre du pieu, ainsi qu'au bout de la pile. La vue ressort des expériences d'un grand nombre de tests sur le terrain, fondés sur divers résultats obtenus avec des capteurs développés par nos soins; sur les pieux battus, laissés en place sur les pieux préinstallés, sur et en profondeur du sol à différentes distances radiales dans le volume du sol à côté du pieu entraîné. Le transfert de vibrations au sol à l'interface pieu-sol se résume au mouvement du pieu, conséquence de la manière dont la force motrice pénètre dans le profil entraîné. Les résultats du mouvement du pieu observé dans le champ sont présentés, montrant les effets de la vibration du pieu à la fois verticalement, horizontalement et transversalement, et comment le mouvement du profil entraîné est connecté au mur de palplanches adjacent qui est mis en mouvement et transfère donc le sol à proximité.

Keywords: vibratory driving; sheet pile; dynamic motion of sheet pile; ground vibrations

1 INTRODUCTION

During vibro-installation of slender *steel sheet piles* (SSP) in soil deposits typical the region of Stockholm Mälardalen, several problems can occur. The aim of the present study is to define situations, why they occur and how vibrations are transferred from the driven SSP to the soil and further in-to the ground.

The paper presents results and experiences based on analysis of several full-scale field tests, [1.], [3.], [5.], and [11.], that have provided insight into the complex motion pattern of vibro-driven SSP's, and how these motions are transferred to the soil volume adjacent to the driven pile. The vibration level in the soil increases three to five times when driving sheet piles into dense soil deposits. Due to hard driving situations, it's often challenging to maintain induced ground vibration levels below stated limits during construction.

The understanding of the complex pile-soil-interface behavior is an important aspect when predicting the induced soil vibration levels attributed to the dynamic lateral movements of the slender sheet pile (and SSP wall) during the installation phase, [4.]. With knowledge and understanding of the key mechanisms (lateral as well as axial movement), of the slender profiles, their intricate geometry as well as for the eccentric loading conditions, it's possible to take measures to keep vibration levels below the limits stipulated in the contract.

2 VIBRO-DRIVING FUNDAMENTALS

The operational principle of vibrodriven sheet piles is visualized in Fig.1. To the left **a.)** a view of a single U-profile, the first to form the pile wall. With driving force F_d, soil resistance along shaft R_s and R_t at the toe together with a bending moment M_{x1} along the neutral axis at the head of the pile causing the profile to vibrate laterally. To the right **b.)** a view of the steady state lateral cyclic motion when the profile is driven into interlock of a pre-installed wall. With driving force F_d, resisting force along shaft R_s, at the toe R_t and in the interlock R_c together with two bending moments M_{x2} and M_y at the head.

The two forces; F_d and R_c, acts eccentrically on the profile, which causes the slender profile to vibrate laterally and transversally in a complex manner, [1.], the lateral motion is transferred to the pre-installed sheet pile wall, as illustrated in Fig.1b.

2.1 Equipment operation

Driving equipment used during the full-scale field tests consisted of leader mounted hydraulic vibrators, extensively described in; [3.], [7.] and [8.]. Operation control of equipment consists of variation of driving frequency and eccentric moment as well as inclination of leader/pile in order to achieve an optimal installation process.

With *optimal* defined as; high rate of penetration (read: vibro-driveability) and low levels of induced ground vibrations.

2.2 Pile-/wall motion

The first SSP profile is driven singularly and the rest in interlock, as illustrated in Fig.1. Both vertical as well as lateral vibrations are transferred to soil as well as to adjoining SSP wall causing motion of both pre-installed wall as well as adjacent soil.

2.3 Soil motion

Soil motion adjacent to the two situations; **a.)** to the left and **b.)** to right in Fig.1, will produce different wave patterns in the soil volume, [6.], a pattern related to the motion of the slender SSP and/or SSP wall, as shown in Fig.3.

2.4 Instrumentation

To get an insight and understanding of the complexity of the dynamic soil-structure interaction when vibrodriving SSP into the ground. An instrumentation system for vibration analysis during vibratory sheet pile driving was developed, described in [2.] and [7.].

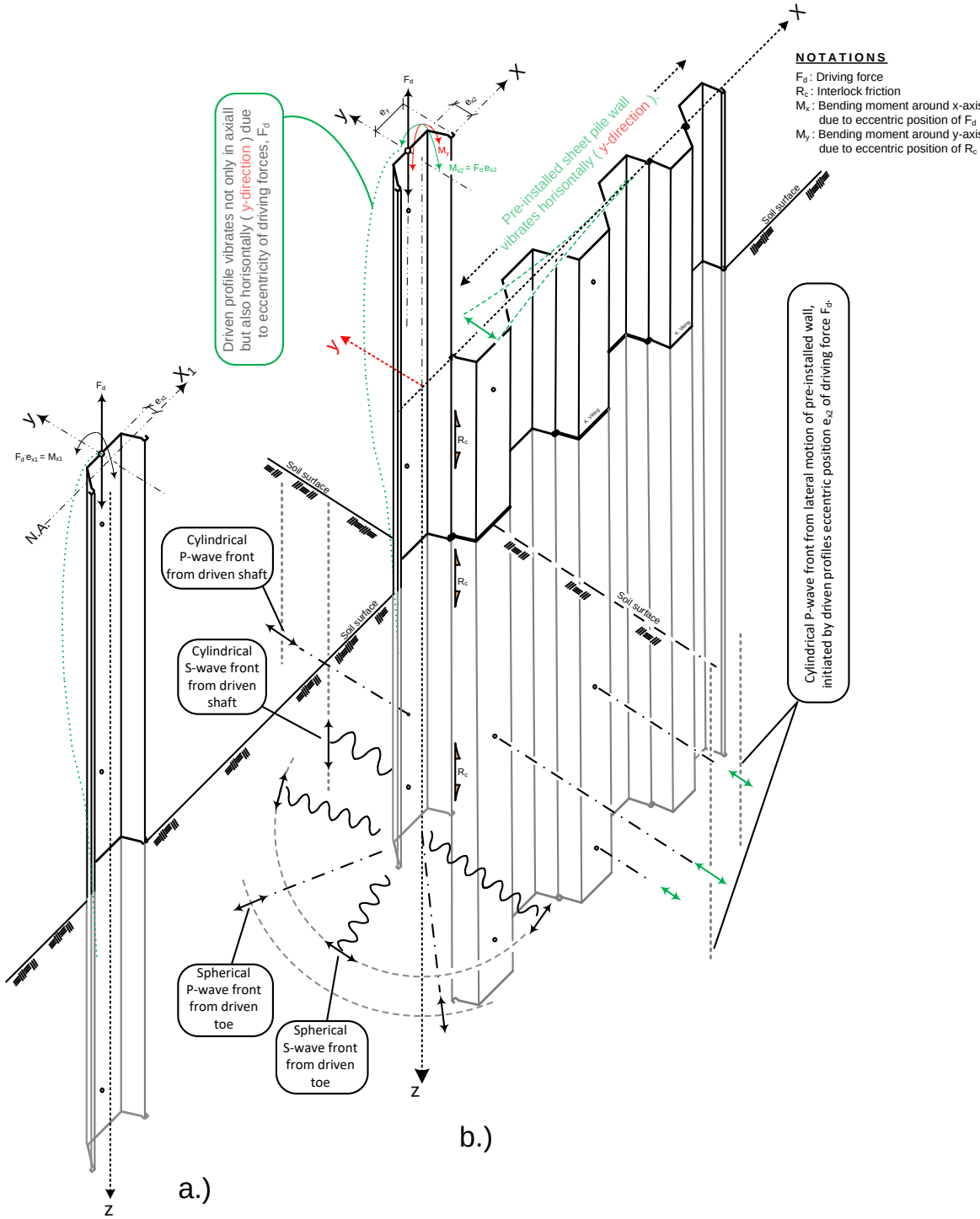

Figure 1. Simplified view of the dynamic vibro-structure-soil interaction mechanism of vibro-driven sheet piles, a.) singular pile, b.) with effects of friction in interlock, after [1.].

3 ANALYSIS AND FIELD RESULTS

Vibration records from conducted full-scale field tests using sensors mounted on driven SSP as well as pre-installed SSP wall and in the soil volume close to the SSP's, [4.], [5.], [9.] and [10.], have provided valuable insight of the excessive motions of the driven profile as well as mechanisms of how motions are transferred to the adjoining sheet pile wall via interlock and further into the soil.

Fig.2 illustrates schematically how ground vibrations emanating from a singularly driven SSP, (situation **a**.) in Fig.1) would give rise to wave patterns in the soil at different elevations of the soil volume as the SSP slides by the three position of sensors MP1 to 3. The axes illustrate the lateral vs. the vertical velocity.

In MP1 the pattern would suggest mainly shear waves from the shaft. In MP2 the round pattern suggests that it's a combination of P-waves from the toe and S-waves from the shaft. And MP3 displays a pattern suggesting mainly P-waves emanating from the toe. This analysis or view of wave pattern in the soil is supported by former presented theory regarding vibration transfer from piles by [5.] and [10.].

3.1 Results

Fig.3 shows results from recorded ground vibrations are plotted against each other, [3.]. The first row shows results from a singularly driven SSP in clay, i.e. situation **a**.) in Fig.1 and the second row displays results from an SSP driven in interlock and entering the till, i.e. situation **b**.) in Fig.1. The presented velocity curves show patterns when only effects of shaft are presented, i.e. toe is sufficiently far from the sensor's level, (as MP1 in Fig.2) so the measurements are to be considered mostly shaft-induced.

Result to the left of the *upper row*, shows the three-directional wave pattern with little polarization.

Results to the left in the *lower row*, on the other hand shows an erratic wave pattern, explained by the effects of the eccentricity of the

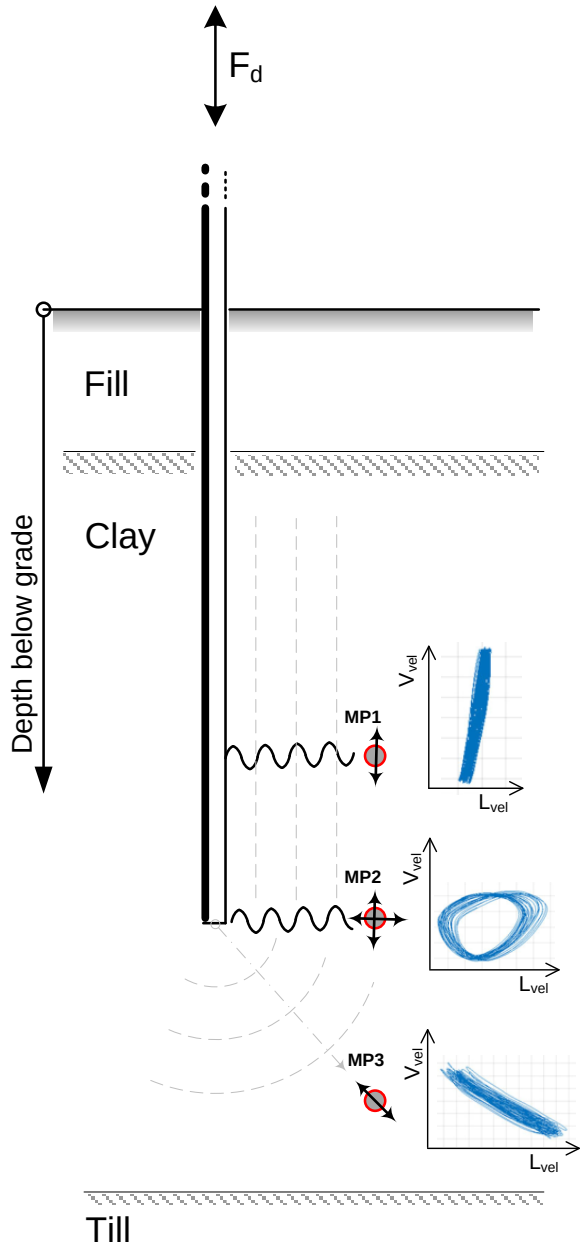

Figure 2. Schematic of the ground vibrations in depth below of single SSP motion, after [6.].

two forces, F_d and R_c, that max out when pile toe at the same time enters the dense till layer.

The other four graphs illustrates the lateral L_{vel} versus the vertical V_{vel} velocity.

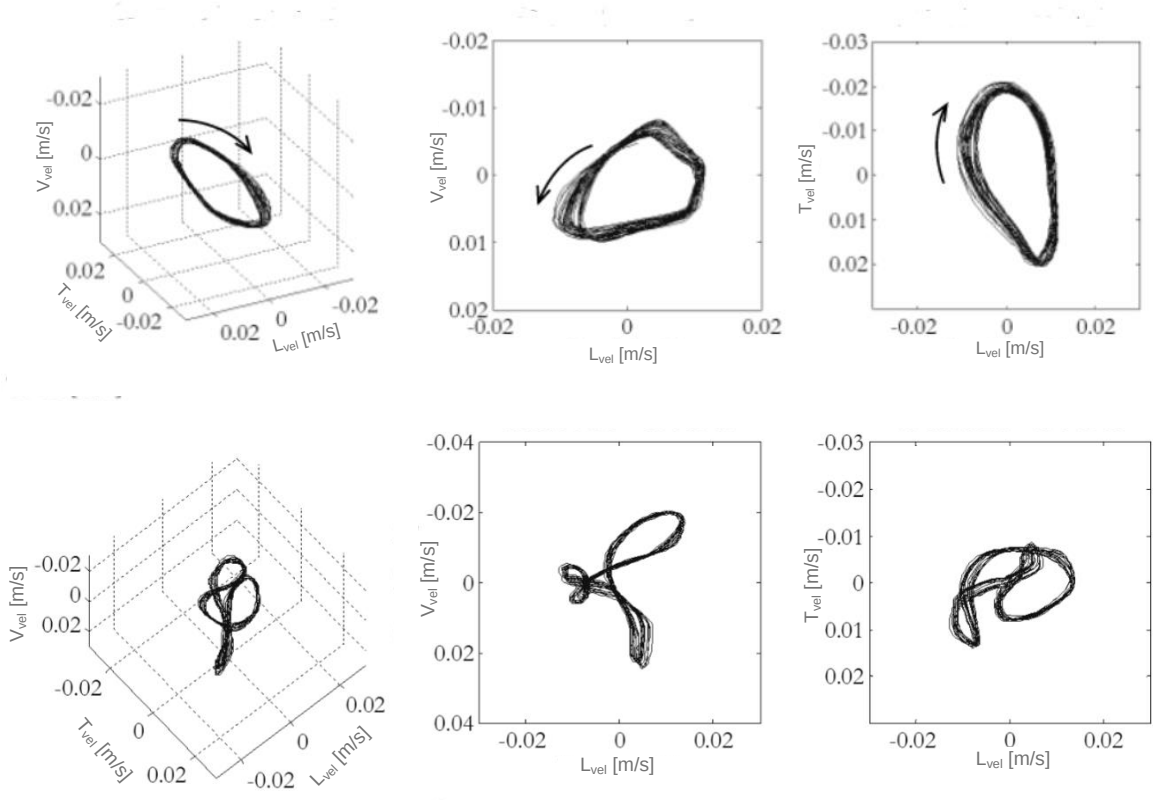

Figure 3. Shaft related ground vibrations; row above: -soil motion of easy driving (clay) of a singular SSP, row below: -soil motion during hard driving (till) including effects of clutch friction, after [3].

4 SUMMARY AND CONCLUSIONS

This paper presents a brief background of the conducted research of induced ground vibrations from vibrodriven sheet piles. Furthermore, a simple principle of the dynamic pile-soil-wall-inter-action is presented.

Results, experiences and analysis of several full-scale field tests have provided insight into the complex motion pattern of the SSP's, and how the motion is transferred to the soil adjacent to the driven sheet pile.

The wave pattern curves during smooth driving, (clay) of a singular pile displays a three-directional pattern with little polarization. However, with effects of clutch friction present, and hard driving, the wave pattern curves becomes more erratic, due to the higher frequency overtones as an effect of the eccentricity of driving force and friction force in the interlock. The motion remains three-dimensional, however with approximately equal magnitude of; vertical-, longitudinal- as well as transversal components.

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