SOIL STRUCTURE INTERACTION ANALYSIS OF THE SETTLEMENT FREE SLAB OF THE HIGH SPEED RAIL LINK IN THE NETHERLANDS

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ABSTRACT

In the western part of the Netherlands, the design and construction of the supporting structures of the new high speed rail link has been started in the year 2000. It is expected that the high speed rail link will be in operation in the year 2006. Due to the soft soil conditions, the track is mainly supported by a piled foundation. One of the supporting structures along the line exists of a concrete slab founded on piles on an approximately 4.5 metres high constructed embankment (the so-called Settlement Free Slab, SFS).

For the analysis of the lateral resistance of this structure under horizontal loads and deformations, the non-linear behaviour of the embankment and subsoil, including the pile group effects, play an important role.

This paper describes the applied design method, in which the soil-structure interaction analysis has been split into the following main analyses:

- Foundation Analysis
  One section of the Settlement Free Slab, between the expansion joints, with a length of 35 metres, has been considered as a pile group. The pile forces and displacements under various loads and load levels have been determined with a suitable pile group programme (SPLICE). The stiffness of the concrete structure is modelled with the help of a stiffness matrix. As the pile group programme assumes a horizontal ground level, the effects of the slopes of the embankment on the lateral resistance of the foundation have been determined by a separate analysis and taken into account as a reduction of the P-Y curves.
- Structural Analysis
  The pile top forces and displacements determined with the pile group model, are used to determine equivalent linear dummy piles, which have been used in the linear structural model. The applied formulae have been given in this paper.

The main design criteria, the construction method, and the evaluation of the pile slab connection detail have also been addressed in this paper.

1 INTRODUCTION

After years of studies and preparatory activities, the contract for the design and the construction of the supporting structures of the high speed rail link in the Netherlands, the so-called HSL-Zuid, was awarded in June 2000. The high speed rail link will extend the already existing high speed rail link in France to the North and is expected to be in operation in the year 2006. The Dutch part of the new constructed track runs from the Belgium border near Breda to Schiphol airport in the centre of the Netherlands. The total length of the track is approximately 100 km [see Figure 1.1]. The Client, being the state of the Netherlands has awarded three main contracts related to the high speed rail link.

1. The design and construction of the supporting structures for the rail system (the sub-structures);
2. The design, construction, finance and maintenance of the rail system (including mechanical, electrical and instrumentation), the super-structure
3. The concession for the operation of the high speed train.

As the rail track is mainly crossing the delta-area in the Netherlands, the subsoil exists of a layer of clay and peat of approximately 10 metres thickness, overlaying the pleistocene sand layer, which in most cases is used as foundation layer for de piled foundations in the Netherlands. Due to these soft soil conditions across the line, and the very strict limitations of the deformations of the rails, approximately 90% of its total length has been founded on piles. Alternative foundation methods like soil improvement were considered in the past but were abandoned for technical and/or economical reasons.

Figure 1.1

The high speed rail line comprises various tunnels, bridges, cuttings and viaducts. However, if no such particular structure is required, a so-called settlement free slab (SFS) is used. In this paper the design of the SFS, which is situated on a 4.5 metres high embankment, is evaluated. In Figure 1.2, a typical section of the SFS is shown. Each of the two tracks is supported by a concrete slab having a width of 3 metres and a thickness of 0.5 metres and connected to each other by a concrete beam at both ends of the section. The length of the section between the expansion joints is 35 metres. A special concrete dowel at the expansion joint is capable of preventing horizontal differential displacements between the section but allows longitudinal and small rotational movements. Nine pile rows per 35 meter and 4 piles per row support the SFS.

With respect to the required lateral stiffness of the settlement free slab, the reduction of the lateral support due to the slopes of the embankment and the pile group effects in the embankment play an important role. The paper presents the analysis of these soil-structure interaction aspects and the way this is modelled in the structural analysis, as well as a brief description of the pile-slab connection detail. In section 2 and 3, general background information is given of the design criteria, the site conditions and the construction method.

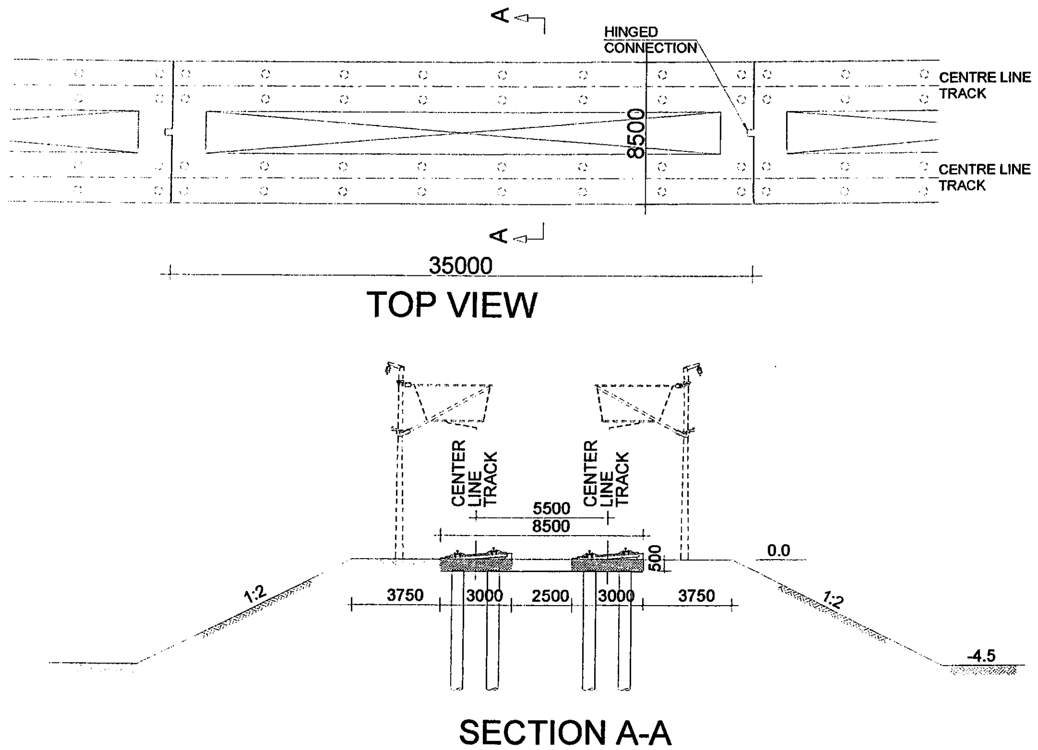

Figure 1.2

2 DESIGN CRITERIA AND TYPICAL SITE CONDITIONS

As the contracts for the construction of the sub-structure and of the rail structure itself were separated, the required performances of the sub-structures were defined by functional requirements which mainly focussed on the interface between the rail system (super-structure) and the supporting structures. The supporting structures shall be able to fulfil the required functional requirements in terms of strength, stiffness and dynamic behaviour for various pre-defined rail systems.

The main functional specifications given by the client are as follows:

- The lifetime of the structure should be 100 years (for parts which are easy to replace, 25 years was specified)
- The structure should be designed for various rail systems, which can be applied over the lifetime, including embedded rail. I.e., the design of the concrete structure should take into account various strength and stiffness characteristics of the rail system.
- The vertical acceleration of the structure under dynamic loading due to a high speed train and a design velocity of 360 km/hour should be less than 1 m/s^2 (comfort requirement).
- The vertical differential displacements at the expansion joints due to the static train loading shall be less than 0.75 mm
- The horizontal differential displacements at the expansion joints due to the horizontal train loads shall be less than 0.9 mm
- The structure shall be designed for a temperature range of +/- 25 degrees Celsius.

A typical soil profile for the existing subsoil in the area under consideration is presented in Table 2.1. The Soil properties of the back-fill soil of the embankment can to a certain extent be defined by the designer himself. However, a narrow range with respect to the acceptable soil properties will of course limit the possibilities with respect to the re-use of available soil from other construction sites. An acceptable wide range was defined with the following soil parameters.

Table 2.1

Soil layer	Depth below SFS [m]	Unit weight [kN/m3]	Drained Phi [degrees]	Cohesion [kPa]
Sand	0.0 - 1.0	17	Range 30 – 35	0
Sandy clay [backfill]	1.0 - 4.5	15	Range 28 - 32	Range 4 - 5
Clay [original top layer]	4.5 - 7.5	15	Range 29 - 33	Range 4 - 5
Peat	7.5 - 9.5	11	Range 20 - 23	Range 18 - 23
Clay	9.5 – 10.7	14	Range 27 - 31	Range 6 - 8
Peat	10.7 – 12.3	11	Range 20 - 23	Range 18 - 23
Sand	Below 12.3	20	Range 32.5 - 35	0

Under the relatively short term loading of a passing train, the soil will mainly behave undrained. Therefore, for the soil layers below the ground water level, the drained parameters with the (permanent) effective soil pressure were used to derive undrained shear strength parameters which were used to determine the lateral resistance of the soil (p-y curves).

3 CONSTRUCTION METHOD

Construction of embankment

The first phase in the construction of the SFS is the construction of the embankment of approx. 4.5 m height. In order to increase the consolidation rate of the soft subsoil, vertical drains are installed in a mesh of 1m by 1m. The embankment is constructed in layers of 0.5 metres using soil which falls within the pre-defined range regarding unit weight and strength parameters.The layers are compacted to a 95% Proctor density.

Driving foundation piles

After approximately 6 to 9 months in which the main part of the primary settlement takes place, the foundation piles are driven a few metres into the sand layer which provides sufficient vertical bearing capacity.

The foundation piles are driven vertically. Reasons for doing so are:

- Vertical piles have an advantage over raker piles with respect to the installation (production speed)
- In case of raker piles, the remaining primary settlement and the secondary settlement of the embankment would cause a soil pressure on the piles (perpendicular to the axis of the piles) introducing bending moments in the piles.

In this design, the foundation piles are cast in place piles having a diameter of 510 mm. These piles are made by driving a closed-ended steel tube into the subsoil to the required penetration level, installing a reinforcement cage into the hollow tube and finally pouring the pile whilst the steel tube is pulled-out using a vibrating hammer.

Construction of the concrete slab
The concrete slab is constructed in a conventional way. The piles are fixed into the slab. As the reinforcement is predominantly loaded by fatigue loads, the reinforcement steel fixing is done without the use of structural welds or tag welds, to ensure that the fatigue strength of the reinforcement is not reduced by welding.

Installation of the horizontal dowel at the expansion joints.
A concrete dowel structure (with most probably UHMWPE as infill material) is made at each expansion joint. It allows movement in the longitudinal direction and a small rotation but no lateral differential displacements at the expansion joint between the concrete slab sections. This hinge structure is required to meet the very strict requirements regarding the differential horizontal displacements being 0.9 mm maximum.

4 DESIGN PHILOSOPHY SOIL-STRUCTURE INTERACTION

Design criteria such as "durability" and "dynamic behaviour of the structure/passenger comfort" were dealt with during the design process by means of separate analyses but these are not elaborated in this paper. This section focuses on the soil-structure interaction analysis and how the non-linear foundation behaviour is modelled in the structural analysis.

At the start of the project there was a strong preference to analyse the structural behaviour of the concrete structure and the foundation piles using a well-known linear structural finite element programme. However, it was obvious that one of the most important design aspects of the Settlement Free Slab (SFS) was an appropriate modelling of the complex and non-linear soil-structure interaction behaviour. This was achieved by splitting the soil-structure interaction analysis in two main analyses, namely:

- Foundation Analysis in which the pile-soil-pile interaction including the effects of the slopes of the embankment was analysed.
- Structural Design in which the stiffness of the foundation was modelled with the help of equivalent dummy piles.

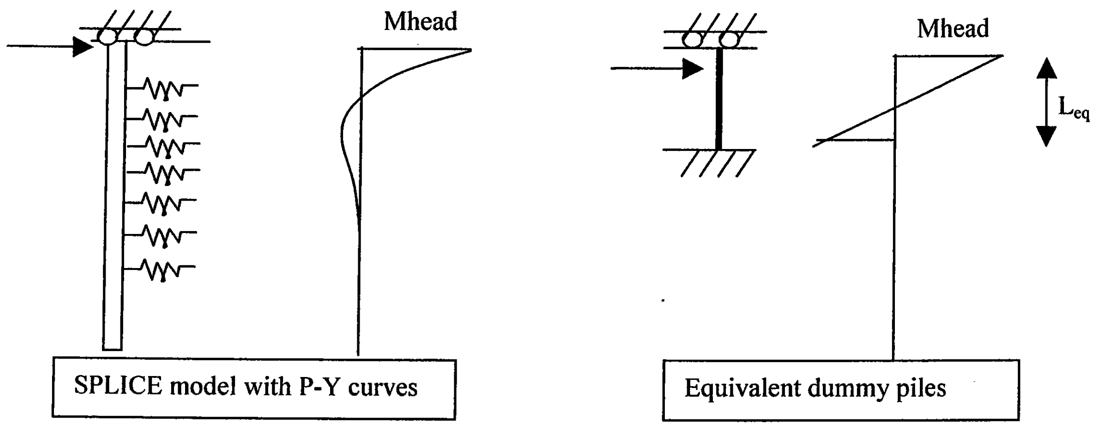

Figure 4.1

This has resulted in a design philosophy, which is schematically shown in Figure 4.2. In the subsequent sections, each of the main steps is discussed in more detail.

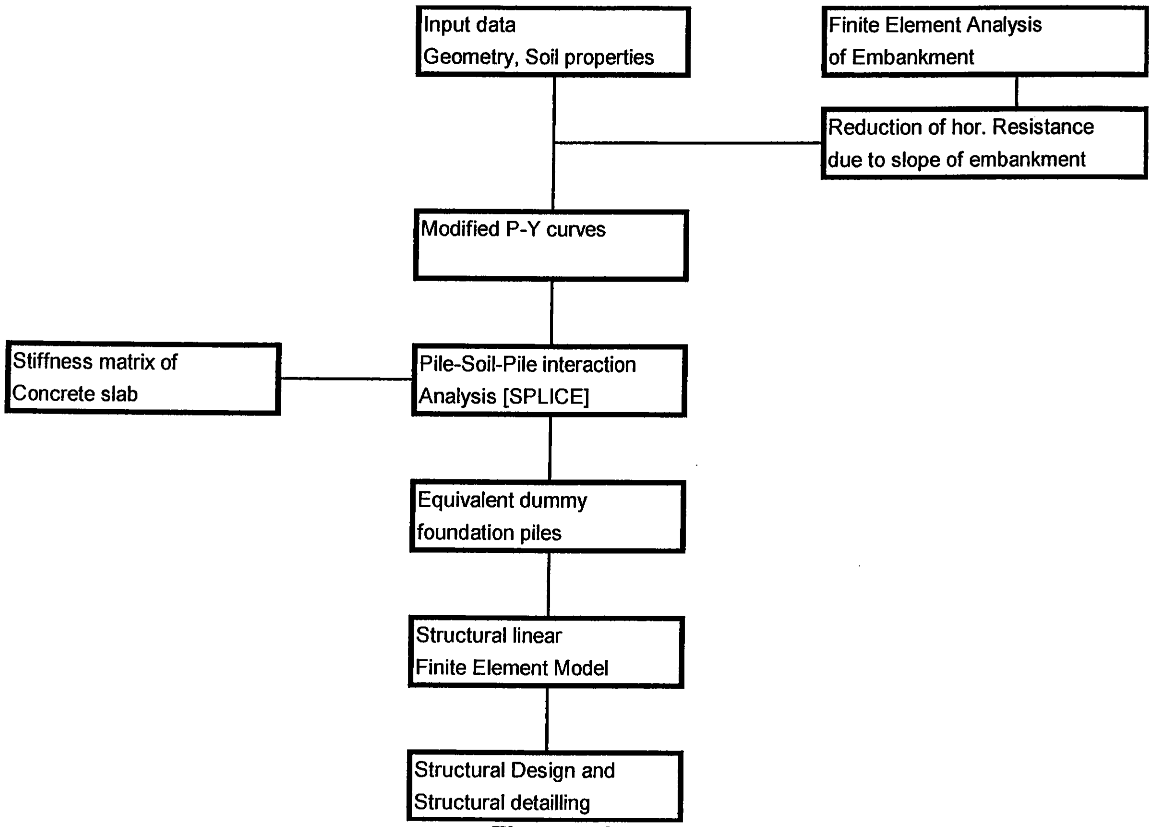

Figure 4.2

4.1 Pile-Soil-Pile interaction analysis

Because of its vertical foundation piles, the horizontal resistance of the SFS mainly depends on the lateral soil resistance of the embankment. As the spacing of the piles in transverse direction is fairly small, pile group effects play an important role. After an extensive evaluation of possible methods to predict the pile group effects, it was decided to use the programme SPLICE [1]. SPLICE is a 3D computer model which is capable to analyse piled foundations including pile group effects. This programme is well known in the offshore industry. The lateral support of the soil is modelled by p-y curves (presenting the horizontal force as a function of the horizontal displacement) according the recommendations of the American Petroleum Institute [2]. The lateral displacement of the SFS is small, which means that the load-displacement behaviour is mainly in the elastic zone. Therefore, the pile group effects do not influence the soil failure capacity and the pile group effects can effectively be analysed with an elastic model. Pile group effects are analysed by integration of the Mindlin point load solutions for an elastic half-space [3]. This method is described by Poulos [e.g. 4]. The stiffness of the superstructure (i.e. the concrete slab) is represented by a stiffness matrix of [6n*6n], where n is the number of piles.

4.2 Reduction of lateral support due to the slope effect

A complicating factor in this respect is that SPLICE assumes a horizontal groundlevel. Because of the relatively small width of the embankment, the effects of the slopes on the lateral resistance cannot be neglected. Therefore, calculations were made, including Finite Element Analyses, to predict the reduction of the lateral support, which was translated in a reduction of the p-y curve. In Figure 4.3, the reduction as a function of the distance from the outer foundation pile to the slope is presented. For further analyses, a reduction of approximately 10% on the lateral support and stiffness was taken into account based on the distance of the outer pile to the slope of the embankment being 4.5 metres.