Design Sequence on The Base on Numerical Simulation and Experimental Testing of a Plane Frame Under Deformations of Piled Foundations

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Abstract. In the paper the stress/strain state of a big-span transversal frame has been investigated. The frame has been acted by external loads and also by vertical and horizontal displacements at support joints. The frame has been selected from a real facility, built in Lithuania. Ground around the piles is soft, under piles toe the ground is the dense sand. Vibrated cast-in-place type of piles has been selected. Pressure of the steel pipe into the ground using the vibrator has been applied for installation. Each pile consists of two parts: the upper part is of 600 mm diameter and 2 m length, the last one of 380 mm diameter. After pile mounting the steel shell of the pipe is pulled out. In the paper some results of pile tests and distribution of stress/strain parameters of the frame under-ground and over-ground structural members are presented and analysed.

Keywords: Design sequence, numerical modelling, pile testing, plane frame, piled foundations

Conference topic: Design experiences and theoretical solutions

Introduction

The entertainment buildings designed for 1000 or more visitors are of special interest among structures of civil engineering. In this case the task of the architects and engineers is selection of the most efficient solution with due to account of aesthetic, functional, structural and other characteristics of a specific building to be designed in order to demonstrate its original application.

In the paper the investigation of a transversal frame of an indoor slope of the complex facility “Skiing slopes with snow pavement in Druskininkai, Lithuania” is presented (Fig. 1).

Fig. 1. A general view of the skiing slope facility in Druskininkai, Lithuania

According to functional application the facility is divided into three main zones: an indoor skiing slope of 422 m length (202 m of which pass over ground, the rest – over the slab); an outdoor skiing slope of 512 m

length (338 m over ground, the rest over the slab); children skiing slope of 2000 m² area. The most deepened overground part of the structure is located at the building local altitude of –29.0 m, the highest one – at altitude +51.0 m. Dimensions of the complex facility in plane are about 425×200 m. The construction is divided into 8 main temperature deformational blocks. During usage of the facility the temperature in indoor and children skiing slopes should be kept at a level of –5 °C the whole year round.

According to current Eurocodes and Lithuanian design codes the service life of the facility is 100 years, a class of responsibility RC3 (LST EN 1990). The facility is of framework type, the main step of transversal frames is 12 m. The frame has 51,5 m bay, columns with foundations and columns with a truss of the frame are rigidly jointed, the middle height of the frame (depending on an angle of the slope along facility) is about 1/3 of the bay (Fig. 2). For the columns and foundations the concrete class C30/37 is adopted in the calculations, for the trusses and purlins – the steel class S355. Stiffnesses of all structural members are specified. Climatic exposures to the facility correspond to the code requirements (LST EN 1991), temperature actions have been considered because of division in temperature blocks. The technological affects from the special equipment are rather considerable only in local zones. Factors of safety on actions and materials as well as the ratios of loading combinations are taken according to the current codes (LST EN 1991; LST EN 1992; LST EN 1993; LST EN 1997).

While designing facility of considerable dimensions in plane it is evident that to perform analysis of the mechanical state not sufficient using a single-stage algorithm as an assumption about simultaneity of actions and

a response reaction produces essential disagreement in comparison with the equilibrium mechanical state of the real building. Such a kind of constructions should be researched stage-by-stage providing for analysis of the intermediate data about structural features and improvement of the decision. Conclusions about structural state and efficiency of variations should be made on the basis of comparing results obtained in the various models with different assumptions. Of course, the most effective a comparison between numerical simulations and natural testing results because of possibility to check general hypotheses and assumptions for individual conditions on a building site.

Fig. 2. A principal calculation model of a transversal frame of the indoor slope

In geomorphologic meaning the building site is placed near (about 100 m) river Nemunas. At the site a real difference of ground initial surface altitudes (elevations) is about 40 m (from +80,8 to +114,4 absolute values). The building site is covered by 0.2–2.5 m layer of backfilled soils. In places silt is found up to 1.6 m depth. Under silt peat is found up to 3.0 m depth. Under the backfill from small grain sand to gravel, soft and semi-rigid clayey sands and hard sandy clays are found. For example in pile test place package of soil layers consists of backfilled clayey sand and peat up to 3.5 m, sandy silty clay till is up to 6.7 m, sand is up to 7.8 m, sandy silty clay till is up to 10.7 m and dense sand is up to 14 m (Fig. 3).

Decided to install cast-in-place diameter of 380 mm piles after analysis of support reactions of preliminary over-ground structures calculations. Piles that has to have big carrying capacity of lateral force has pile head of 2 m height and 600 mm diameter. Lower part of the pile is of 380 mm diameter. Sand of medium density that has $q_c = 12,0$ MPa, dense sand that has $q_c = 15,0$ MPa and stiff sandy clays that has $q_c = 15,0$ MPa are the base of cast-in-place. Length of the piles is varying from 5 to 8 m and is revised according to response of vibrating and actual package of soil layers (Tomlinson, Woodward 2008).

Fig. 3. Package soil layers and CPT in pile test place

Vertical bearing capacity of cast-in-place vibratory piles is calculated (LST EN 1997, Kelevišius *et al.* 2013). Lateral bearing capacity of the cast-in-place piles is calculated too (DIN 4085 2007), using Vesic (1961) sub-grade reaction modulus formula.

Technology of pile installation

Technology of vibrated cast-in-place type of piles installation is presented (Fig. 4). Sequence of pile installation is given below:

- positioning the steel pipe on the cover;
- vibrating the steel pipe into the ground;
- vibrating down to the projected depth;
- installing the reinforcement cage into the pipe;
- filling in the concrete.

Fig. 4. Technology of vibrated cast-in-place pile installation

Fig. 5. Theoretical results of pile calculations: maximal bending moment 184 kNm; maximal shear force 100 kN; maximal horizontal displacements 31 mm

The concrete is compacted during the extraction. Advantages of vibrated cast-in-place piles are (Gabrielaitis *et al.* 2012):

- high performance since the pipe is vibrated into ground as one piece;
- due to the sealed designing neither ground water nor soil can get into the casing of the pile to be installed;
- the displacement of soil and the vibration causes an improvement of the ground directly adjoining the pile;
- reinforcement cage and concrete are installed into dry steel pipe in a short time;
- exact determination of the pile length and diameter according to the geological and static conditions.

Analitical displacement of laterally loaded piles

Lateral displacements of piles have been calculated (DIN 4085; Buß 2010a, 2010b) by software GGU LATPILE. Subgrade reaction modulus has been determined by using Vesic (1961) formula (Ashford 2005):

$$k_h = \frac{0.65 \cdot E_s}{1 - \nu^2} \cdot 12 \sqrt{\frac{E_s \cdot d^4}{E_p \cdot I_p}}, \quad (1)$$

where: E_p and I_p are a modulus of elasticity and a moment of inertia and of a pile; E_s – a modulus of elasticity of a soil; d – a pile diameter; ν – Poisson's ratio. Using formula (1) values of a subgrade reaction have been found (Table 1).

Table 1. Values of subgrade reactions

Soil	Value, MN/m³
Backfilled soils	4.0
Sandy silty clay, till, plastic	1.5
Sand	4.2
Sandy silty clay, till, hard	22.3
Dense sand	15.0

Some stress/strain parameters of the calculated pile are presented (Fig. 5).

Design values of settlements while piles were under vertical loads have been defined until 15 mm, values of horizontal displacements in case of horizontal action are to 20–36 mm. Characteristic values of loads on the pile are: axial force of 690 kN, shear force of 100 kN.

Methodology of pile lateral loading tests

Systems for a horizontal loading, measuring horizontal force and displacements have been installed between reaction pile and test piles cap (Fig. 6). Systems included: loading jack, manometers (or load cells) for measuring forces and displacement gauges. Horizontal loads have been increased by stepwise (Wu, Hamada 2000; Martinus *et al.* 2014). Each horizontal load has been kept constant for 5 minutes before applying a next step of the horizontal load. For each step of horizontal load readings of horizontal displacements have been recorded after 1, 5, 10, 20, 40 minutes. Each load has been kept constant until the relative stabilization and has been reached equal to no more than 0.1 mm per 20 minutes. Unloading process has been done also stepwise recording pile cap horizontal displacements.

Fig. 6. A loading system for testing of groups of two piles connected by pile cap

It is determined by tests, that horizontal displacements are of 6.0 mm and 9.3 mm of structure of two piles, which are connected between reinforced beam, when structure is loaded by 100 kN horizontal static design load. According to theoretical calculations the value of horizontal displacements is 31.3 mm. It is determined by tests, that vertical displacements are 8.3 mm and 12.1 mm of one pile when pile is loaded by 1000 kN vertical static design load. Noticed, that test results of pile horizontal and vertical displacements (Fig. 7) are smaller than theoretically calculated ones (Reese, Van Impe 2001; Tumosa 2006; Tumosa, Stragys 2008).

Fig. 7. Pile vertical (a) and horizontal (b) load/displacements dependents

Investigation of design variants

It is not enough to test one pile for describing pile foundation (i.e. pile and pile cap above) because stress/strain state is more complex – the distribution of stress is influenced by stiffnesses of structure.

Two different cases are investigated because there are different geological situations and distributions of support reactions: it is needed to install 8 piles in axis A and 6 piles in axis E (Fig. 8). Connections of all piles with plates are rigid. Pile cap's height is of 1.5 m.

Fig. 8. Plane of a piled foundation of the transversal frame

Every foundation is investigated using four cases of a pile calculation model (Fig. 9).

Piles are modelling by:

- statically determinate system;
- statically indeterminate system when support nodes are fixing;
- finite elements, which are modelling as piles with elastic spring–connection in vertical direction at the bottom;
- finite elements, which are modelling as piles with elastic end–springs in vertical direction at the bottom and horizontal subgrade–connections along.

There are two important aspects for significant influence of bending moment of column (Samofalov *et al.* 2010, 2015; Mandolini *et al.* 2013; Popov 2015):

- investigation of stress distribution between piles under one pile cap;
- investigation of influence of an elastic base.

In first case it was assumed that pile caps is rigid body. During solving of other three problems pile caps and piles have been simulated using accordingly shell and beam finite elements.

It is assumed that discrete model is more realistic when in calculation model piles are modelled also. However, in this case increases the number of assumptions, that is why error of idealisation becomes dominant and can distort calculation results. So, analysis of results should be based on practical experience of engineering solving of situations. A final decision about an influence of foundations to an upper–ground construction can be made during solving a problem „frame/foundation/frame“ (Fig. 2).

Mechanical state of the transversal frame

Mechanical state of the transversal frame on elastic foundations are interesting just for comparing with primary ones, when becomes clear its practical benefit of modifying of calculations model. So, by investigations of the transversal frame of the indoor slope the following variants of calculations have been considered:

- 1) transversal frames, pile caps and piles are calculated separately (Fig. 9a);
- 2) pile cap is calculated separately from upper–ground part that are fixed at pile joint nodes (Fig. 9b);

- 3) pile cap is calculated separately from upper-ground part, pile cap is based on upper side of the pile only on bottom node springs (Fig. 9c);
- 4) pile foundation on horizontal elastic springs along and on the bottom node is calculated separately from upper-ground structure (Fig. 9d);
- 5) the frame with foundations of 2nd variant;
- 6) the frame with foundations of 3rd variant;
- 7) the frame with foundations of 4th variant.

Fig. 9. Foundation models: statically determinate (a) and indeterminate (b), with springs (c) and subgrade (d)

Calculations results of variants are reactions and displacements of piles (Fig. 10), which are presented by normalised values (μ , from 0 to 1, and δ , from 0 to 1) on the normalised pile length scale (λ , from 0 to 1).

Comparison of variants showed significant differences. Both displacements and bending moments distributes very different via pile length. In cases of pile cap with piles on elastic subgrade modelling using finite elements (4th and 7th variants) top of the pile will become less bended in most loaded top of the pile (difference comparing with single pile is respectively 17% and 42%) and that is why displacements are smaller (last variant differs by 51%).

Fig. 10. Bending moment (a) and lateral displacement (b) distribution along a pile shaft. Signs 1, 4 and 7 show the numbers of calculation variants

After investigations it can be noted, that calculation of big-span transversal frame by separate parts can not reflect the mechanical state of that structure. Modelling foundations on elastic subgrade the possibility appears to compare results that quite differs from primary ones and mostly depends on assumptions of interaction of pile and soil. Various cases of foundation calculations have not significant influence on the truss. Modelling of traverse frame with pile in calculation scheme is favourable because it reduces materials. Investigation of the piles is increasing reactions of pile plate that is important for safety

of structure. Reactions in piles are reducing when calculation model of transversal frame with piles is investigated.

Conclusions and recommendations

On the basis of above-presented investigation results the following conclusions and recommendations have been briefly drawn:

- on of the most important factor during untypical designing is an estimation criterion, so results of a natural testing can help us to understand a physical meaning of the problem, such kind of data is very interesting for a practical engineer – in case of original building we should try to organize an experiment;
- in case of valuable bending moments and complex foundations it is recommended to simulate together under-ground frame with foundations, because engineering assumptions play a very significant role for results;
- an exact estimation of mechanical state parameters is significant in many engineering applications as an example for optimization problems (Atkočiūnas, Jankovski 2011).

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