INTERACTIVE GEOTECHNICAL DESIGN OF BRIDGE FOUNDATIONS

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Abstract: *The paper presents the role and the importance of interactive approach to geotechnical designing of bridge foundations. Interactive geotechnical design means that the project design of foundations, and maybe even of the bridge itself, based on investigation works, should be corrected or changed while taking into consideration the results of stress and strain measurements of the main foundation and of the bridge during the construction.*

Interactive geotechnical design is shown on the example of the "Krapinčica" viaduct, which was constructed as part of Zagreb-Macelj highway project. Pile foundations were designed first. After the construction of piles, bearing capacity testing was carried out on the piles, which turned out to be unexpectedly low. In order to prevent the ground from breaking and to prevent excessive viaduct deformations, ground improvement method Jet Grouting was used to improve stiffness and bearing capacity of the pile ground. Furthermore, sliding micrometers were inserted into the piles and they enabled the monitoring of vertical strain of the piles and of the ground. Measurements were conducted with the sliding micrometer in several stages of the viaduct construction. It was established that the state of viaduct deformations had been within project assumptions and no additional methods for ground improvement or for the basic viaduct construction were necessary.

Interactive geotechnical design shown in this paper gives to Foundation Designer and to Bridge Designer the quickest, the safest and the most rational way of intervening into the existing design.

1. INTRODUCTION

The Krapinčica viaduct was built as a part of the Zagreb-Macelj highway construction project. Its foundations are bored piles, 6 piles per one bridge pier, 120 cm in diameter and 9 to 11 m long.

Dynamic bearing capacity testing of the piles was conducted after the construction of piles, and they showed unexpectedly low bearing capacity of piles on S1, S2, S3 and S4 bridge piers, which means lower bearing capacity than it had been predicted in the project.

S1 and S2 piers were repaired with the Jet Grouting method by constructing Jet Grouted columns underneath every pile, about 120 cm in diameter, 3.5 to 4 meters deep.

Geodetic measuring of all ground displacements were conducted on S3 and S4 piers, and also relative deformations in the depth of piles were monitored during the viaduct construction. By using such measures, and with a known module of pile concrete elasticity, it is possible to define the distribution of longitudinal forces along the pile, or to distinguish the distribution of pile skin friction and forces on the base of the pile, and also to define, from the known pile load, which part of the force is transferred by the pile cap construction.

Measurements were conducted with the sliding micrometer and special measuring tubes built into the pile and further into the main ground 15 m deep.

Samples were taken out of boreholes underneath the piles, and laboratory testing was conducted with the purpose of defining the optimal ground improving procedure in case of excessive strain appears in any viaduct construction phase, and in case of unwanted distribution of the pile load, or in case that rehabilitation of these piles becomes necessary.

2. INERACTIVE GEOTECHNICAL DESIGN

Interactive geotechnical design [1,2,3] gives the possibility of project modification during construction based on in situ measurements that give information on the real behavior of soil and on the state of the construction as well, with the aim to secure stability, security and economy of the designed structure. Deformeters and inclinometers for measuring vertical and horizontal displacement of the main ground are used for foundations of heavy infrastructure structures, bridges, dams etc. Measurement results are used for back stress-strain analyses analyses in which, with the appropriate selection of main soil deformation characteristics, measured and calculated displacements are coordinated to the acceptable engineering accuracy. These analyses give real deformation characteristics of the soil and also the real state of stress, or forces in the main construction. Next stability analysis is conducted, and it gives also the real factor of safety. Multiple advantages for the project are achieved with back analyses. Except for real parameters and safety factors, it is possible to have an insight to the need of using additional measures, such as ground improvement by jet-grouting or constructing additional piles that would improve the first project solution and secure structure stability during construction and exploitation.

With interactive geotechnical design we are given not only a safe and economical solution for the structure, but also important knowledge on real material behavior.

3. DYNAMIC PILE BEARING CAPACITY TESTING

Bearing capacity dynamic testing of the piles is based on measurements of strain and pile acceleration caused by an impact of relatively heavy load (Figure 1). Load weight is 1-2% of the expected static pile bearing capacity. Height from which the load is falling is 0.5-3 m. Two or four strain measuring devices and two or four acceleration measuring devices are put onto the pile shaft, on the depth of at least 2 pile diameters. Dynamic pile forces are calculated according to strain measurements and the assumed elasticity module, while velocity can be achieved by integrating acceleration.

By using the numerical analysis, based on the one-dimensional wave equation, and from measured forces and velocities, we can define dynamic bearing capacity of the pile. The analytic procedure is known as the Case Method. The Case Method has been developed at the Case Institute of Technology in Cleveland, Ohio, in the United States, and it the result of a thirty-year-long research. With this procedure bearing capacity dynamic testing has entered the American ASTM D945-89 Standard (Standard Test Method for High-Strain Dynamic Testing of Piles).

Testing is conducted with a device called the Pile Dynamic Analyzer (PDA). PDA is a portable device used for measurements, conditioning, filtration and signal analysis. It also has a portable computer that can analyze and present measured values in real time. The measured data are saved to the hard disc and then post-analyzed in order to define the static pile bearing capacity. Numeric analysis is conducted with the CAPWAP Program (Case Pile Wave Analysis Program) [4,5]. Ground characteristics are assumed, and according to the numeric model hammer-pile-ground velocity, or forces in the pile, can be calculated. The given signal can be compared to the measured signal. Ground characteristics are changed until the measured and calculated signal is not equal to the adequate engineering accuracy. After corresponding signals static bearing capacity of the piles is calculated, as the sum of the pile skin friction and the bearing capacity of the pile base.

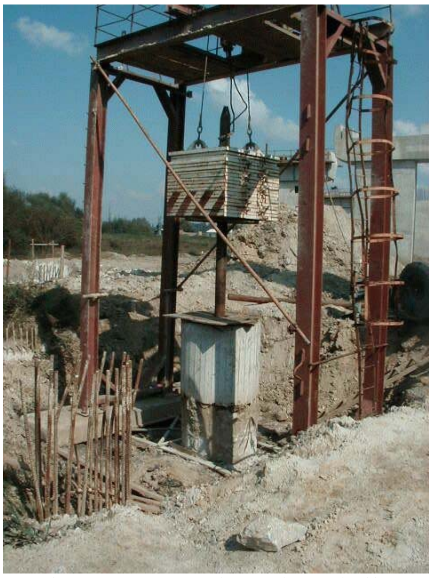

Figure 1: Dynamic testing of piles

4. SOIL IMPROVEMENT BY JET GROUTING METHOD

With the development of civil engineering, we have been often dealing with lack of ground that has adequate characteristics for construction, so we have to build on bad and unfavorable soil. There are many construction technologies used in such cases, and lately the Jet Grouting method has been developed [6,7,8].

The Jet Grouting is method where extremely high pressure is used, usually 300 to 700 bars, or 30 to 70 MPa, for putting energy into the fluid that is pumped into the soil at about 250 to 330 m/s. High fluid speed is used for breaking or cutting the soil structure, moving of particles and their mixing with the grout material (Figure 2).

There are three traditional jet grouting systems. Selection of the most appropriate system is generally a function of the in situ soil, the application, and the physical characteristics of soilcrete required for that application. However, any system can be used for almost any application providing that the right design and operating procedures are used.

Single Rod Jet Grouting (Soilcrete S) **-** Grout is pumped through the rod and exits the horizontal nozzles in the monitor with a high velocity, approximately 200 m/sec. This energy causes the erosion of the ground and the placement and mixing of grout in the soil. Single rod jet grouting is generally less effective soils.

Double Rod Jet Grouting (Soilcrete D) **-** A two-phase internal rod system is employed for the separate supply of grout and air down to different, concentric nozzles. Grout is used for eroding and mixing with the soil. The air shrouds the grout jet and increases erosion efficiency. The double rod system is more effective in cohesive soils than the single rod system.

Triple Rod Jet Grouting (Soilcrete T) **-** Grout, air and water are pumped through different lines to the monitor. High velocity coaxial air and water form the erosion medium. Grout emerges at a lower velocity from separate nozzles below the erosion jet. This somewhat separates the erosion process from the grouting process and yields a higher quality soilcrete. Triple-rod jet grouting is the most effective system for cohesive soils.

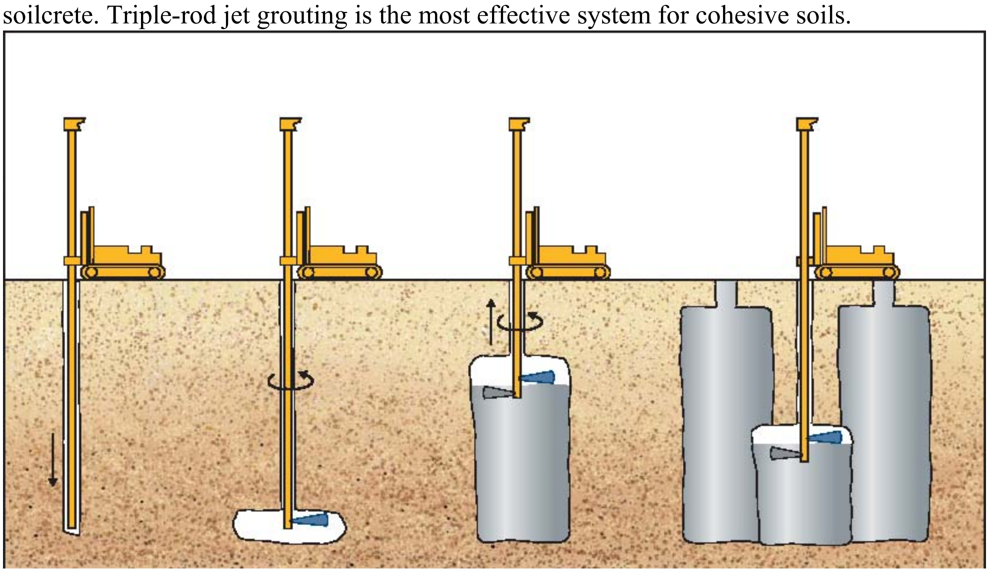

Figure 2: Jet Grouting procedure

5. MONITORING PROGRAM

Monitoring program predicts measurements of changes in vertical strain along the pile, or monitoring of longitudinal force changes and pile skin friction during the construction of the viaduct. Measurements are predicted for piles S3D-P5, S3L-P2, S4D-P2 and S4L-P2.

Measurements of vertical pile strain and of the main ground with the sliding micrometer are based on measurements of relative strain of special PVC tubes built into the pile and in the ground, ϕ51/63 mm in diameter [9,10]. Tubes are 1 m long and they are connected with special telescopic connectors ϕ67 mm. Connectors are telescopically deformed and in this way they enable measurements of relative deformations. Tubes are inserted with the grouting method into boreholes 15 m long, ϕ100 mm in diameter.

Measurements are conducted with the sliding micrometer. The sliding micrometer was developed at the Swiss Federal Institute of Technology, Zürich (ETZH) and it was manufactured by the company Solexperts LTD, Schwerzenbach, in Switzerland. It is 1 m long, ϕ47 mm in diameter, ± 0.001 mm/m sensitivity, ± 0.003 mm/m precision in terrain conditions and also ± 5 mm/m measuring range.

Taken into consideration that the sliding micrometer tube had been built into one pile per bridge pier, the measured pile strain is considered equal for all piles in the pier, and longitudinal forces in piles and skin friction were summed up for all six piles within one pier.

Figure 3 shows the plan view of the S4L pile cap with position of installed sliding micrometer.

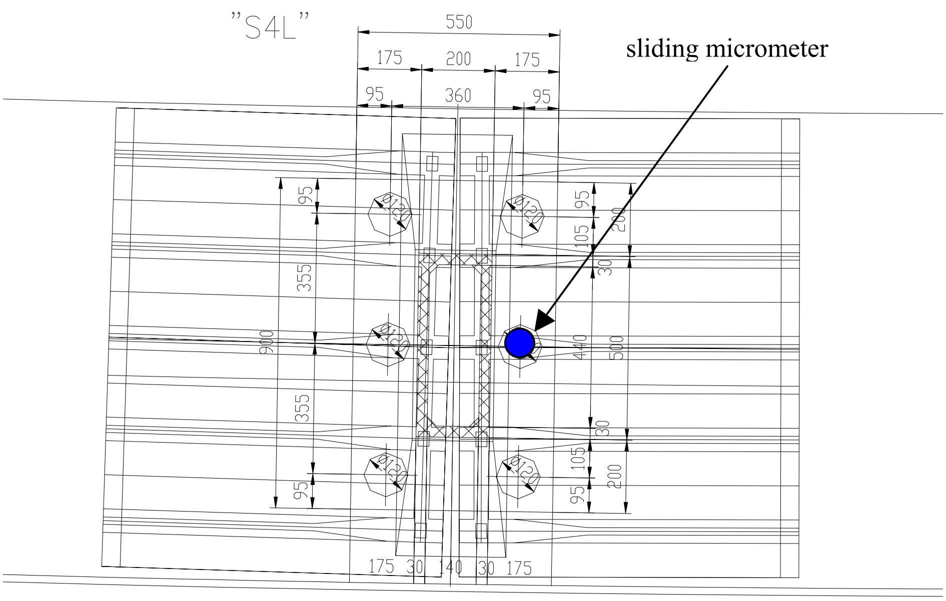

Figure 3: Position of installed sliding micrometer

Table 1 shows measurements of load distribution between piles and pile cup at the end of the viaduct construction.

Bridge pier	Load (kN)	Pile cup construction (%)	Pile base (%)	Skin friction (%)
S3D	11724	34	21	45
S3L	11724	25	31	43
S4D	11821	33	20	47
S4L	11821	33	28	39

Table 1: Load distribution at the end of the viaduct construction.

Figure 4 shows the changes in vertical strain and displacements along the pile at the end of the viaduct construction.

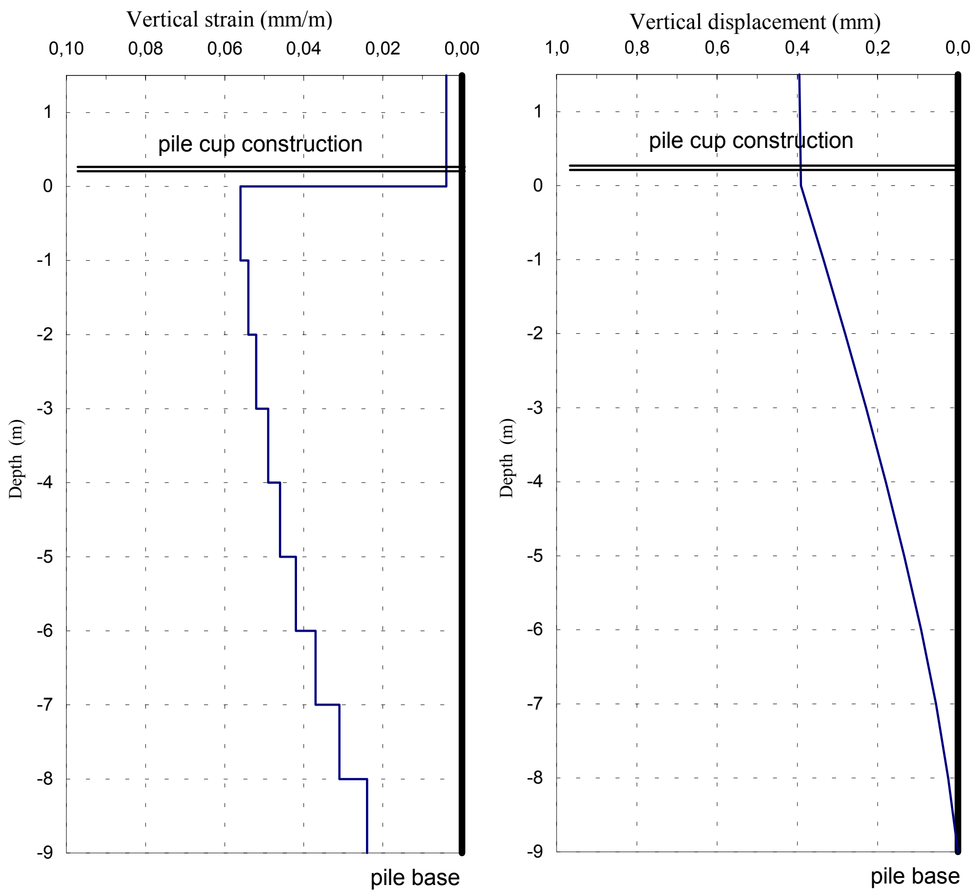

Figure 4: Vertical strain and displacements at the end of the viaduct construction

Figure 5 shows the changes in longitudinal force and pile skin friction along the pile at the end of the viaduct construction.

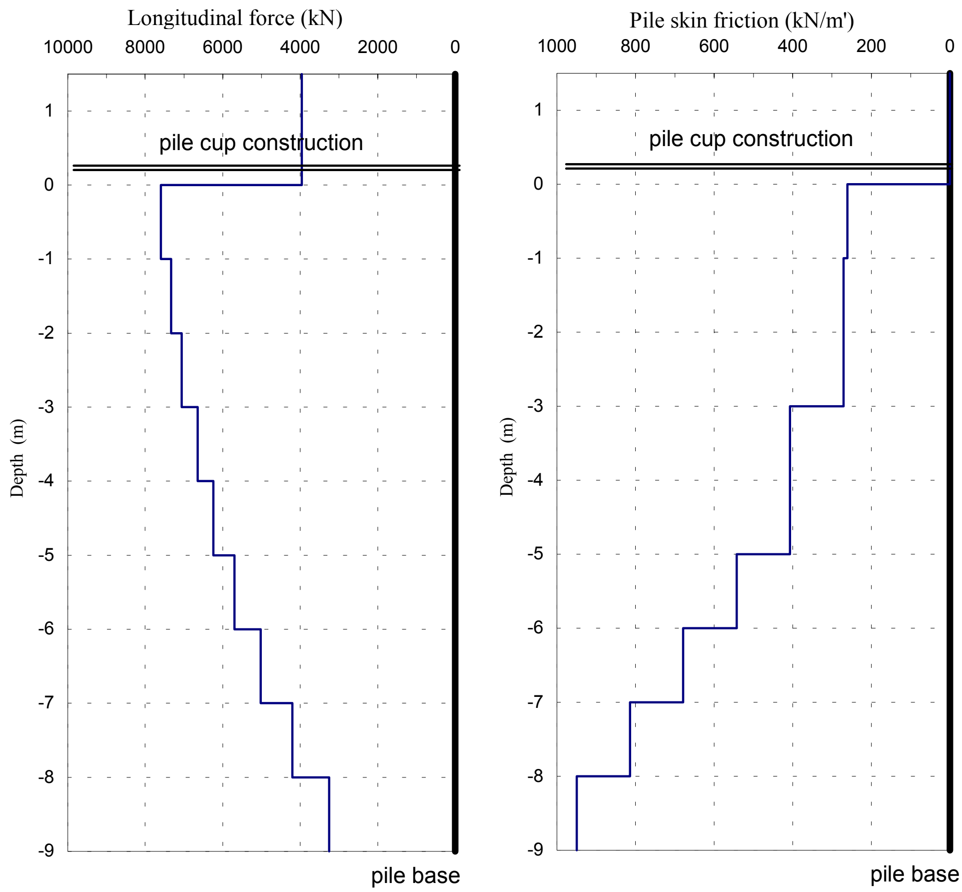

Figure 5: Longitudinal force and pile skin friction at the end of the viaduct construction.

6. CONCLUSION

Laboratory research testing has shown that the ground underneath S3 and S4 piers is relatively adequate for the Jet Grouting ground improvement method, in a way it was conducted underneath S1 and S2 pile group.

Measurements with sliding micrometers have shown that piles in S3 and S4 piers, at the moment of the highest load, take over 65-75% of total load, which is about 1450-1700 kN.

Dynamic testing of pile bearing capacity on piers S3 and S4 have shown that piles can take over maximum force about 2500 kN.

Tested pile bearing capacity is 1.47-1.72 times higher than the real pile load.

Based on all measurements and testing it can be concluded that reinforcement of pile groups S3 and S4 is not necessary.

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