ISSN 1330-3651
UDC/UDK 624.046:627.333]:519.876.5

TESTING THE LOAD-BEARING CAPACITY OF HARBOUR NO. 5 IN THE PLOČE PORT

Meho Saša Kovačević, Krešo Ivandić, Danijela Marčić

Preliminary notes

The paper presents the methodology and results derived from testing the harbour loading capacity. A numerical model for the system incorporating the head beams, RC slabs, piles and soil was formulated. Presumptions were made concerning the stiffness characteristics of the RC slabs, piles and foundation soil, and the rotations of the head beams and RC slabs were calculated for the given loadings. Clinometer carriers that permitted measuring of the rotation angles of the RC slab for the previously defined loading scheme were placed on the RC slab of the harbour structure along the previously defined line. The calculated and measured rotations were compared for various loading schemes. A numerical back-analysis was conducted in order to determine actual stiffness characteristics of the system. The loading was numerically simulated until achieving breakage of the foundation soil under the piles and reaching the load-bearing capacity of the RC harbour structure.

Keywords: *clinometer, harbour, load-bearing capacity, numerical back-analysis, soil-structure interaction*

Ispitivanje nosivosti obale 5 u luci Ploče

Prethodno priopćenje

U radu su prikazani metodologija i rezultati ispitivanja nosivosti obale. Formiran je numerički model sustava naglavna greda-AB ploča-pilot-tlo. Pretpostavljene su krutosne karakteristike AB ploče, pilota i temeljnog tla, te su za zadano opterećenje računati zaokreti naglavne grede, odnosno AB ploče. Na AB ploču obalne konstrukcije, postavljeni su, duž unaprijed definirane linije, nosači klinometra koji su omogućili mjerenje kutova zaokreta AB ploče za unaprijed definirane režime opterećenja. Uspoređeni su, izračunati i izmjereni zaokreti za razne režime opterećenja. U cilju dobivanja stvarnih krutosnih karakteristika sustava provedena je povratna numerička analiza. Numerički je simulirano opterećivanje do sloma tla ispod pilota, odnosno dosezanja nosivosti AB obalne konstrukcije.

Ključne riječi: *interakcija tla i konstrukcije, klinometar, luka, nosivost, numerička povratna analiza*

1 Introduction
Uvod

Harbour 5 is the largest and most important harbour in the Ploče Port. It was constructed in 1966 and consists of a reinforced-concrete (RC) harbour structure and harbour areas. The RC structure has a total length of 508,00 m and a width of 23,15 m.

Its foundation lies on RC Benotto piles with a 120 cm diameter. The piles have been placed extending all the way to the load-bearing gravel layer that is situated at a depth of approximately 38,00 m. The RC structure was constructed as five modules with dimensions of 92,40 × 23,15 m. The mutual axial distance of the piles in the longitudinal cross-section is approx. 10,0 m, while in the perpendicular cross-section their axial distance amounts to 7,0 and 6,0 m. A total of 50 × 4 = 200 Benotto piles were constructed. The piles are mutually connected using 2,40 m high head beams, secondary RC head beams and a 40 cm thick RC slab.

Within the scope of works in repairing harbour 5, works were carried out on repairs to the jackets of damaged RC Benotto piles and the top connections of the Benotto piles and head beams. As required by the main design project, repairs to the jackets of the first three rows of Benotto piles were carried out, including repairs at the top of the piles connecting the head beams where damage existed. In accordance to the Sea Ports Act, it was deemed necessary to determine the greatest permissible loading for the harbour 5 RC structure. The cross-sectional characteristics of the harbour structure are shown in Fig. 1.

2 The testing procedure
Postupak ispitivanja

Two typical cross-sections were chosen for conducting testing of the load-bearing capacity for the piles and RC harbour structure. The cross-sections were chosen at module 2 and module 4. These two profiles were chosen due to the fact that module 2 was the least damaged or had very little damages prior to repairs, while module 4 had the most damages or was very heavily damaged prior to undertaking repairs.

A numerical model was formulated for the system incorporating the head beams, RC slabs, piles and foundation soil. Stiffness characteristics of the RC slabs, piles and foundation soil were taken as presumptions, and for the given loading, the rotations of the head beams and RC slab were calculated.

Clinometer carriers, which enabled the measurement of rotation angles for RC slabs using previously defined loading schemes, were placed at the RC slab of the harbour structure at both investigated cross-sections, along the previously defined line. The rotation angle meters are placed so as to measure rotation angles at each metre length of the RC slab. By integrating the rotation angles, the deflection line of the RC slab was obtained. The rotations of the RC slab depend on the mutual relationship between the RC slab, the Benotto piles and foundation base. Measuring of the rotation angles is conducted using measuring devices called clinometers.

The calculated and measured rotations of various loading schemes for both investigated cross-sections were compared. Once again, a numerical model was implemented using altered system stiffness while the measured and calculated values for rotation of head beams

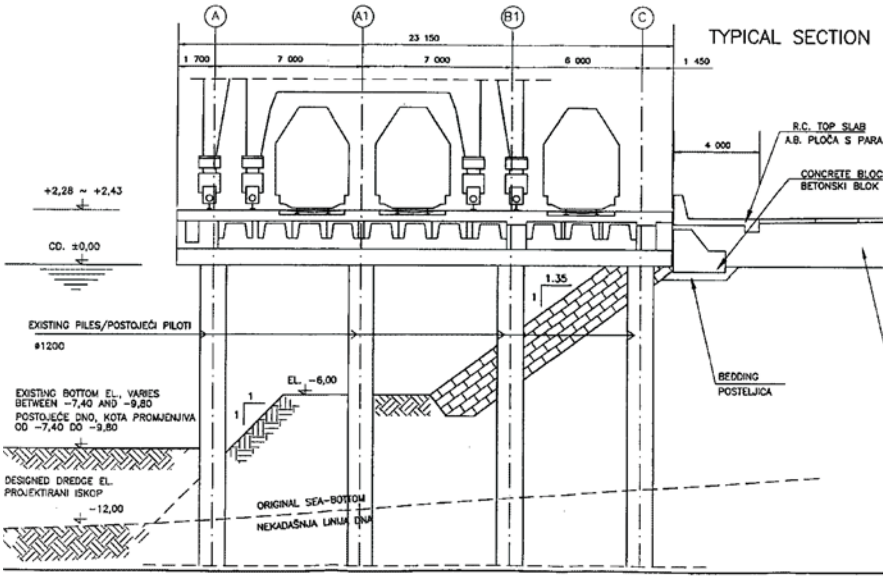

Figure 1 *Characteristic cross-section of the harbour structure*
Slika 1. *Karakteristični presjek obalne konstrukcije*

and RC slabs did not coincide in an engineering-like precision.

The load-bearing capacity and permitted loading of the piles and RC harbour structure were determined using actual system stiffness characteristics. A numerical simulation of loading leading up to the breakage of the pile foundation base and obtaining the load-bearing capacity of the RC harbour structure was conducted.

2.1 Loading of the harbour structure
Opterećivanje obale

Loading of the harbour structure was conducted using existing 20 cm thick, 2 × 2 m concrete slabs. The weight of a single slab was 2 tonnes. A total of 96 slabs were used for a single measured profile. The slabs were laid out so as to ensure a uniform distribution of load on the cross-section under investigation, i.e. allowing the loading to be successfully numerically simulated using a 2D model (Fig. 2). Placement of the slabs was carried out using a forklift (Fig. 3).

In the first instance, at specific intervals, 4 × 4 slabs were positioned. The area onto which loading was transferred amounts to around 95 m^2. The loading was conducted in successive placements of 6 rows of slabs, whereas the measuring was carried out following placement of the 1^{st}, 2^{nd}, 4^{th} and 6^{th} row of slabs. Numerical simulation and determination of actual system stiffness characteristics incorporating head beams, RC slabs, piles and foundation soil was conducted on the basis of results of these 4 measurements for both tested modules.

Figure 2 *Loading of the harbour structure with 2 slab rows*
Slika 2. *Opterećivanje obale s dva reda ploča*

Figure 3 *Placement of the loading using a forklift*
Slika 3. *Manipulacija opterećenja viljuškarom*

2.2 Measuring equipment
Mjerna oprema

The quality of conducted measurements depends on the measuring system comprising: measuring equipment, installation and incorporation of measuring equipment, the experience and training of personnel taking the measurements, procedures and conducting of measurements, analysis of measurement results and finally a presentation and the interpretation of the measurement results. The success of geotechnical measurements depends on elimination or the maximum reduction of measurement errors. A measurement error is a deviation of a measured and actual value. The most common errors in measuring are: gross errors, conformance errors, environmental errors, observational errors, sampling errors, systematic errors and random errors [1].

A great number of instruments, from very simple to very sophisticated, have been developed for geotechnical monitoring. The most commonly used instruments are those for measuring displacements (surveying instruments), rotations (clinometers), transversal and longitudinal displacements along the borehole (inclinometers, extensometers, sliding deformeters, sliding micrometers), forces, stresses and strains (various load cells, pressure cells, extensometers) and pore water pressures (various piezometers). Each instrument comes with its own range, precision, resolution, reliability, durability and price, which means that it has advantages and disadvantages. It is then up to the person in charge of the geotechnical project to devise an efficient monitoring plan for the design and to select the monitoring equipment according to project requirements and available resources [2].

Measuring of rotational angles of structures using a clinometer is based on measuring of the rotational angles in a structure possessing incorporated special clinometer carriers. The clinometer carriers are 20 cm long. They are installed into the structure using a particular drilling and injection procedure (Fig. 4).

Figure 4 *Taking measurements using the clinometer*
Slika 4. *Provođenje mjerenja klinometrom*

Measuring is carried out using an inclinometer from the company Solexperts Ltd. Schwerzenbach, Switzerland. The measuring base is 200 mm long, has a sensitivity of ± 0,001 mm/m, a precision under field conditions of ± 0,003 mm/m and a measuring range of ± 20 mm/m. The difference of the read result between two readings represents the rotation of the clinometer carrier expressed in mm/m.

3 Determining the actual stiffness characteristics of the system
Određivanje stvarnih krutosnih karakteristika sustava

Geotechnical measurements in combination with numerical back-analysis contribute to developing an understanding of the behaviour of geotechnical structures and determining their physical and mechanical parameters [3]. Numerical analysis where the material parameters change in accordance with the results of geotechnical measurement is called numerical back-analysis. The principle of the back-analysis is that the state of stress and deformation for the assumed material characteristics are calculated and then compared to the measured field results. Since in the majority of cases the measured results for the assumed parameters do not comply with measurements, it then becomes necessary to alter the material characteristics until the calculated and measured values coincide with an engineering-like precision [4].

Determining the actual stiffness characteristics of the system incorporating the head beams, slabs, piles and soil is conducted using numerical back-analysis. A numerical model is formulated (Fig. 5) and the rotation angles of the RC slab are calculated. These rotations are compared to those measured. The stiffness characteristics of the system are altered until the measured and calculated rotations coincide with an engineering-like precision. The calculations are conducted using the computer programme SIGMA/W developed by the company Geoslope from Alberta in Canada, and utilise a linear elastic-ideal plastic model of the base.

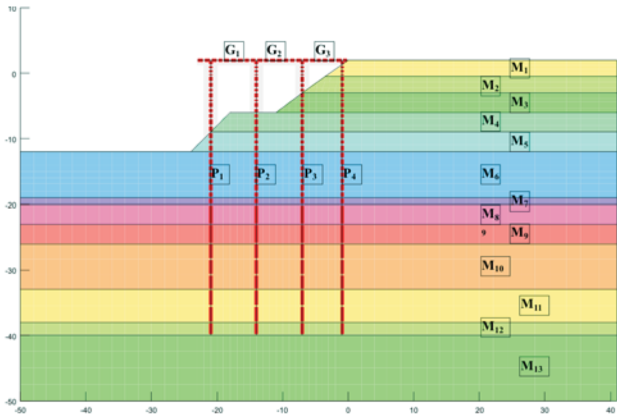

Figure 5 *Numerical model with designations for structural elements and base layers*
Slika 5. *Numerički model sa oznakama konstruktivnih elemenata i slojeva tla*

The head beams and RC slabs are modelled together as elastic concrete structural elements. The width of the beams is taken as 2,0 m whereas the sought height of the beam that will interact with the other elements of the system will provide rotations close to those measured. The height of the beams sought is at intervals of 250 − 300 cm. The characteristics of the beams used in the analysis are presented in Tab. 1.

Table 1 *Beam parameters*
Tablica 1. *Parametri grede*

Beam	Width B / cm	Height H / cm	E / MPa
G1	200	250-300	30000
G2	200	250-300	30000
G3	200	250-300	30000

The piles are also modelled as elastic concrete structural elements. The diameter of the sought piles lies in the range 100 – 150 cm and is to interact with the remaining system elements thus providing rotations closest to those measured. The piles characteristics used in the analysis are presented in Tab. 2.

Table 2 *Piles parameters*
Tablica 2. *Parametri pilota*

Pile	Diameter D / cm	E / MPa
P1	100-150	30000
P2	100-150	30000
P3	100-150	30000
P4	100-150	30000

The soil is described as an isotropic elasto-plastic Mohr-Coulomb's material. The stiffness characteristics of the ground base and strength parameters are not varied in this analysis. In determining the initial stress state, the sea level is taken into account. The ground parameters used in the analysis are presented in Tab. 3.

Table 3 *Ground parameters*
Tablica 3. *Parametri tla*

Material	Depth from-to / m		φ / °	c / kPa	ν	E / MPa	γ / kN/m³
M1	2	–1	30	0	0,33	10000	18,0
M2	–1	–3	0	30	0,45	5400	19,0
M3	–3	–6	35	0	0,33	2000	19,5
M4	–6	–9	0	42	0,45	8100	19,0
M5	–9	–12	0	46	0,45	9500	19,0
M6	–12	–19	0	54	0,45	11800	19,0
M7	–19	–20	0	60	0,45	13700	19,0
M8	–20	–23	0	63	0,45	14600	19,0
M9	–23	–26	0	67	0,45	16000	19,0
M10	–26	–33	0	75	0,45	18400	19,0
M11	–33	–38	0	30	0,33	50000	20,0
M12	–38	–40	15	25	0,33	18000	20,0
M13	–40	–50	40	0	0,33	100000	20,0

3.1 Algorithm for seeking an optimal solution
Algoritam za traženje optimalnog rješenja

In order to obtain an optimal solution or a solution that best approximates the measured results for all loadings, a procedure was carried out which took into account all 4 measurements or measured rotations for all imposed loadings.

Some were designated as measured angles using $\theta_{\mathrm{M}ij}$, while $\theta_{\mathrm{R}ij}$ was used to designate rotation angles such that: i = the position of the measuring location from left to right, i.e. from the sea to the land (i = 1-22) and j = ordinal number for measurements dependent on the loading

$j=1 \Rightarrow$ loading 3,37 kN/m²
$j=2 \Rightarrow$ loading 6,74 kN/m²
$j=3 \Rightarrow$ loading 13,48 kN/m²
$j=4 \Rightarrow$ loading 20,22 kN/m².

An optimal solution is that which provides an optimal value of the sum of the square of deviations of all incorporated clinometer carriers for all utilised loadings. In this way, the measurement results are taken into account for all measuring locations and for all loadings.

$$\text{Optimal solution} \Rightarrow \min \sum_{i=1}^{22}\sum_{j=1}^{4}\left(\theta_{\mathrm{M}ij}-\theta_{\mathrm{R}ij}\right)^2.$$

3.2 Results of the numerical back-analysis
Rezultati povratne numeričke analize

A large number of calculations were conducted. The beam heights (G1, G2 and G3) were altered in intervals of 250 – 300 cm, whereas the piles diameters (P1, P2, P3 and P4) in intervals of 100 – 150 cm. An accuracy of 1 cm was required. The numerical loading was imposed with the same intensity and position as was conducted during the measuring process. The position of the loading is presented in Fig. 6.

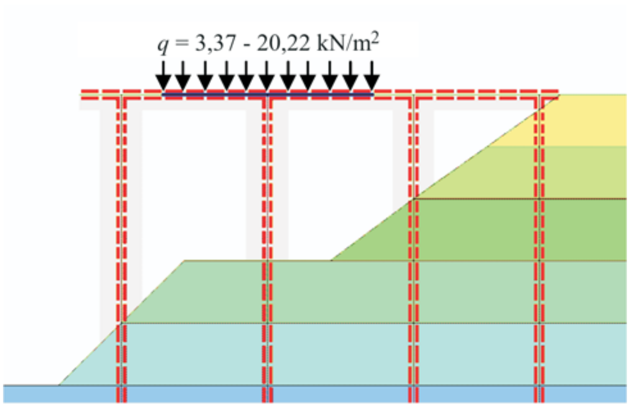

Figure 6 *The loading position in the numerical model*
Slika 6. *Pozicija opterećenja u numeričkom modelu*

Numerical back-analysis provided the beam height and pile diameter as presented in Tab. 4 and 5.

Table 4 *Numerical back-analysis providing the beam characteristics*
Tablica 4. *Povratnom analizom dobivene karakteristike greda*

Beam	Width B / cm	Height H / cm	E / MPa
G1	200	263	30000
G2	200	259	30000
G3	200	257	30000

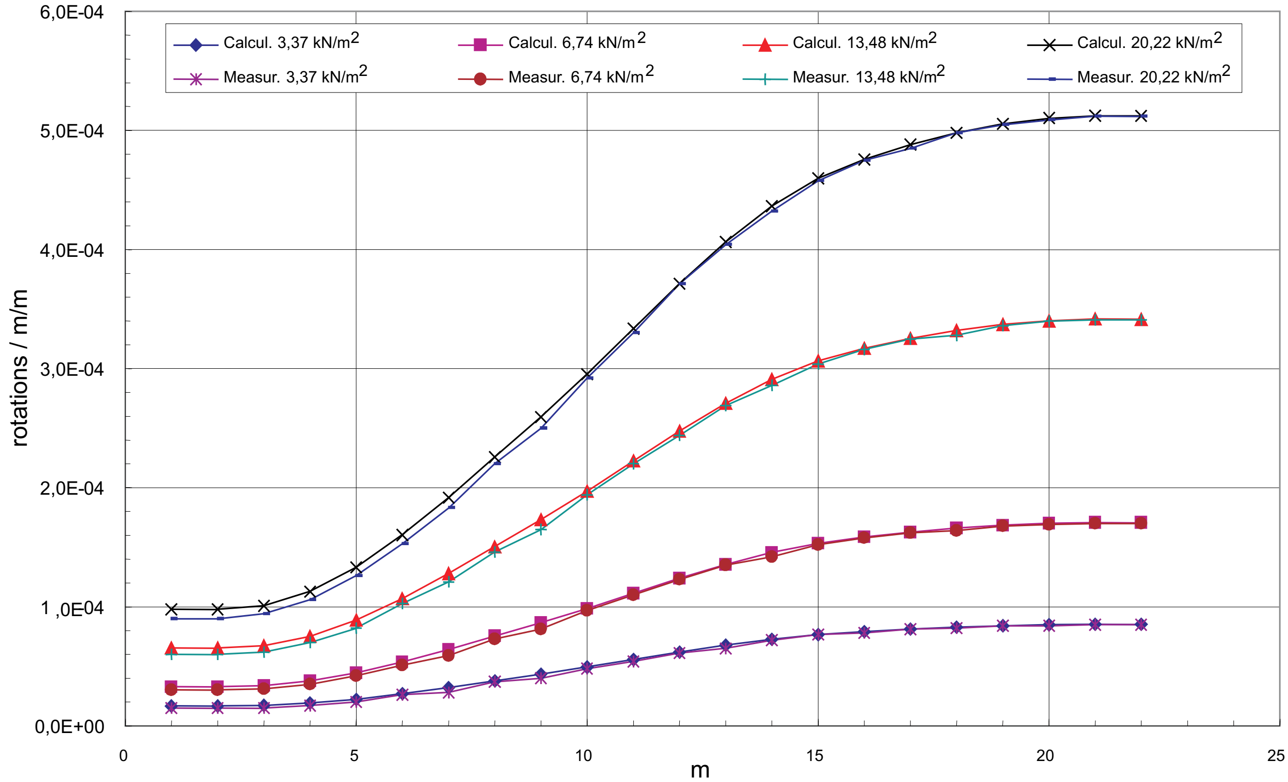

***Figure** 7 A comparison of measured and calculated rotational angles for the harbour structure*
***Slika** 7. Usporedba mjerenih i izračunatih kuteva zaokreta obalne konstrukcije*

***Table** 5 Numerical back-analysis providing the piles characteristics*
***Tablica** 5. Povratnom analizom dobivene karakteristike pilota*

Pile	Diameter *D* / cm	*E* / MPa
P1	114	30000
P2	114	30000
P3	111	30000
P4	111	30000

In Fig. 7, a comparison of measured and calculated rotations for the obtained optimal solution is shown.

4 Determining the load-bearing capacity of the harbour structure
Određivanje nosivosti obalne konstrukcije

Following determination of the actual stiffness characteristics of the system incorporating the beams, slabs, piles and foundation soil, a numerical simulation for loading of the harbour structure leading up to breakage was conducted in order to determine the load capacity of the piles, i.e. the maximum loading capacity that the harbour structure could withhold during use.

The loading was placed across the whole harbour structure and incrementally increased up to the point of soil failure. It commenced with a loading of 1 kN/m^2.

The stress state and deformation of this load were taken as the initial state for the following calculations where the loading was increased by increments of 1 kN/m^2.

In this way, soil failure was achieved under the pile for a load of 60 kN/m^2 for both modules.

According to [5], it is recommended that the vertical permitted loading of the pile should be calculated so that the load can be distributed using an appropriate safety factor.

Furthermore, the loading capacity of the pile determined using the theoretical expressions and parameters for strength from the research papers was recommended to be a safety factor equal to 3, whereas the loading capacity of the piles determined using trial loads or dynamic experiments recommended a lower safety factor equal to 2.

Hence, the permitted load on the Benotto piles amounted to 60/2,0 = 30 kN/m^2, i.e. 3 t/m^2 (in no-SI units).

5 Conclusion
Zaključak

Within the scope of the repair works to harbour 5 in the Ploče Port, works were conducted in repairing the jackets of the damaged RC Benottto piles and repairing the top of the Benotto piles connected to the head beams.

Two typical cross-sections were chosen to conduct testing of the loading capacity for the piles and the RC harbour structure. The profiles were chosen on modules 2 and modules 4. These two profiles were chosen on account of the fact that module 2 had the least damages or was only slightly damaged prior to repairs, whereas module 4 was the most damaged or in other words, it had heavily damages prior to the repairs.

The geometry of the carriers, the quantity of incorporated rebars and quality of steel and concrete conform to the data in the project design documentation. The foundation soil is a Mohr-Coulomb's isotropic elasto-plastic material. The stiffness characteristics of the soil and the strength parameters were not varied in this analysis.

Repairs to the piles were carried out successfully which was shown by the uniform stiffness of the piles (within 5 %) on both measured modules.

Once the actual stiffness characteristics of the system incorporating the head beams, slabs, piles and soil were determined, a numerical simulation of loading of the harbour up to the point of failure was carried out in order to determine the loading capacity of the piles, i.e. to determine the maximum loading that could be withstood by the harbour during its use. It was concluded that the loading capacity of the harbour for both modules amounted to 60 kN/m^2, whereas the maximum permitted loading of the harbour for both modules amounted to 30 kN/m^2.

6 References
Literatura

[1] Dunnicliff, J. Geotechnical Instrumentation for Monitoring Field Performance, John Wiley, New York, 1988, 1993, pp. 250–268.
[2] Kovačević, M. S. The Observational Method and the Use of Geotechnical Measurements // Geotechnical problems with man–made and man influenced grounds, Proc. 13th Europ. Conf. on Soil Mech. and Geotech. Eng., Prague, Czech Republic, August 25-28, Vol. 3, 2003., 575-582.
[3] Kovačević, M. S.; Jurić-Kaćunić D.; Simović R. Determination of strain modulus for carbonate rocks in Croatian karst (In Croatian) // Građevinar, 33, 1(2011), pp 35-41.
[4] Brunčić A.; Jurić-Kaćunić D.; Kovačević M. S. Design and realization of side-cuts in flysch rock mass (In Croatian) // Građevinar, 62, 1(2010), pp 13-23.
[5] Fellenius B. H. Basics of Foundation Design. Second Expanded Edition. BiTech Publishers Ltd. Richmond, B. C. Canada, 1999., pp 164.

Authors' addresses
Adrese autora

Prof. dr. sc. Meho Saša Kovačević, dipl. ing. građ.
Sveučilište u Zagrebu
Građevinski fakultet
Zavod za geotehniku
Kačićeva 26
10000 Zagreb, Croatia
Email: msk@grad.hr

Doc. dr. sc. Krešo Ivandić, dipl. ing. građ.
Sveučilište u Zagrebu
Geotehnički fakultet
Zavod za geotehniku
Hallerova aleja 7
42000 Varaždin, Croatia
Email: kreso.ivandic@gfv.hr

Doc. dr. sc. Danijela Marčić, dipl. ing. građ.
Sveučilište u Zagrebu
Građevinski fakultet
Zavod za geotehniku
Kačićeva 26
10000 Zagreb, Croatia
Email: djk@grad.hr