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**Original Scientific Paper**

# EXPERIMENTAL ANALYSIS OF THE BEHAVIOR OF CAPPING BEAMS ACROSS THE PILES IN LOOSE SAND

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**Abstract**. *The test program was conducted on 1G models capping beams over the tops of the group of 2x2 piles, the purpose of which was to reduce the settlement of the structure. The test program included six experiments, three of which were conducted on capping beams without piles and three on capping beams across the tops of the piles, with pile distances 3d, 4d and 5d, where d is the pile diameter and the pile length is 40 d. Test results show that the current conventional approach to the design of capping beams across the tops of the piles, where the entire load is entrusted to the piles, is too conservative and irrational. Instead, it is more economical to apply a low bearing capacity factor for piles as settlement reducers and maximize use of raft bearing capacity to carry part of the external load.*

**Key words**: *raft foundation, pile foundation, piled raft foundation, settlement, Eurocode.*

## 1. INTRODUCTION

In geotechnical engineering, funding facilities on shallow foundations is not always possible due to the great deformability of the soil. Accordingly, alternative funding methods are used, such as deep funding. The calculation of the pile group is based on the assumption that the entire load from the aboveground part of the structure is taken over by the piles, not taking into account the load-bearing capacity of the capping beam. This approach to calculation is very conservative and irrational – the basic principle of calculation should be based on the fact that the foundation structure contains as many piles as would be needed to reduce settlement to an acceptable level, so that the load from the aboveground structure is transferred over the capping beam to the ground and partly

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over the piles. Such a calculation approach would aim to contribute to the rationalization of the foundation structure, thus reducing the number of piles.

Assuming that the load is evenly distributed over the entire raft foundation, a deflection will occur in the middle of the raft foundation, as schematically shown in Figure 1a. By adding a certain number of piles under the raft foundation, settlement and differential settlement will reduce, Figure 1b. Using piles to reduce settlement is an idea that originated earlier, in the1970s [2]. There is a number of studies that deals with the behavior of cap-ping beams and capping beams across the top of the piles [3], [4], [5], [6], [7] as well as with the settlement of capping beams across the top of the piles [8], [9], [10].

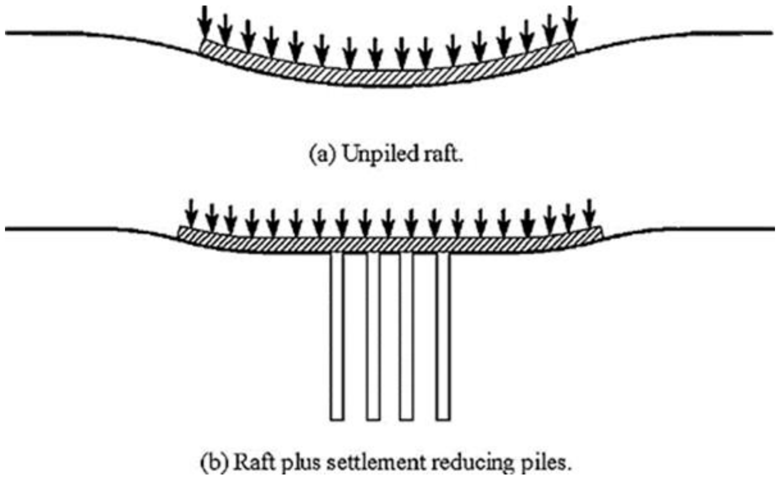


**Fig. 1** Piles required to reduce differential settlement [1]

Muhammad Rehan Hakaro [11] investigated capping beams across the top of the piles in multilayer soil of different stiffness exposed to different loads using a software package Plaxis 2D.

O. Reul and M. Randolph [12] deal with the influences of certain parameters on the load distribution between the capping beam and the piles, such as the number and arrangement of piles, the piles length and the capping beam stiffness. They conclude that when using longer piles there may be less settlement than when using a larger number of piles, and that bending moments in the capping beam cannot be reduced by supporting it with piles. Phung [13] concludes that the conventional practice of designing beams across the tops of the piles is based on the assumption that external load is carried by piles and any contribution of the capping beam is neglected. Therefore, the approach is too conservative because the capping beam carries a significant part of the load due to direct contact with the ground. Bayad and others [14] say that in tests conducted on the capping beams across the tops of the piles 2x2, 3x3 and 4x4, when the capping beam settles 10 mm, 60% of the total load is taken over by piles. Fleming [15] states that when designing capping beams across the tops of the piles, capping beams have an appropriate capacity. Due to not taking into account the contribution of the load-bearing capacity of the capping beam, when designing capping beams across the tops on the piles, a larger number of piles is calculated than is actually needed [16].

Assel Zhanabayeva et al. [17] compared the capping beams on the piles, applying Euro-code 7 and Kazakhstan regulations. Thea concluded that Eurocode 7 was more conservative, provided a higher level of security [18], [19]. The system of foundation of capping beams across the tops of the piles is a fundamental structure that combines the effective bearing capacity of capping beams and piles taking into account the interactions pile-soil, pile-pile, capping-beam-soil, pile-capping beam.

The interaction between soil and structure has an impact on soil behavior as well as the behavior of piles under load [20], [21]. The behavior of the pile-soil system is mostly nonlinear. The load in the horizontally loaded pile is resisted by the pile-ground interaction, which depends on pile diameter, pile material [22]. Bourgeois [23] investigated the influence of the pile-soil interaction in a vertically loaded group of piles.

Based on experimental results, Phung Duc Long and other [24] authors propose a simplified method that can be used in design. The experiment shows that at the beginning of the loading of the capping beam, piles take over most of the load and after reaching the bearing capacity of the pile, the load is transferred to the capping beam. This method can give effective results if used with the finite element method for estimating the settlement of capping beams across the tops of the piles.

In this paper, the results of experimental analysis of 1G model of the capping beam across the tops of the piles, conducted for the purpose of writing a doctoral thesis, were used. The aim of the research was to point out that when designing these types of foundation structures on loose sand, the load-bearing capacity of the capping beam should not be neglected, while the number of piles required to receive vertical force would be reduced and thus a more rational foundation structure would be achieved. Together with the interaction of capping beams and piles, group effect was also examined.

## 2. Materials and Methods

Laboratory tests were performed on a 1g model for a group of four piles, assembled in a 2x2 pile configuration. The test program consisted of six experiments, three of which were performed on piles of length L/d=40, with pile distances of 3d, 4d, 5d, and three experiments with a system of capping beams directly resting on a raft foundation, i.e. capping beams without piles. Pile arrangement, as well as capping beam dimensions, are shown in Figure 2.

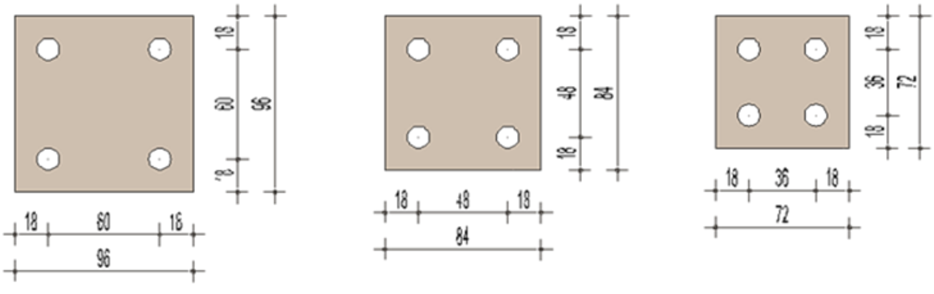


**Fig. 2** Pile arrangement and capping beam dimensions (in mm)

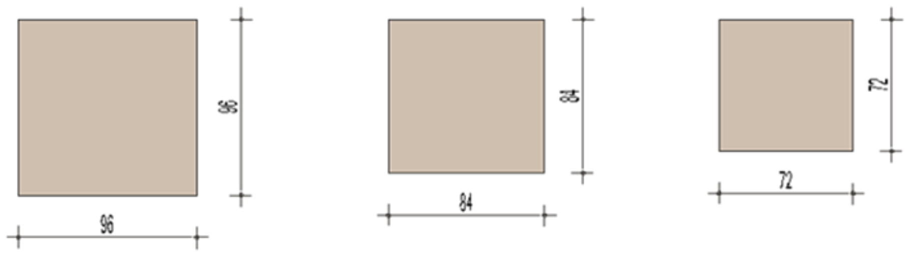


**Fig. 2** Pile arrangement and capping beam dimensions (in mm)

### 2.1 Soil parameters

Dry sand was used in the experiment. Granulometric experiments were performed to determine the granulometric curve of the soil used. The granulometric curve parameters are: D10 = 0.11mm, D30 = 0.15 mm, D60 = 0.23 mm, the uniformity coefficient is Cu = 2.1 and the curvature coefficient Cz = 0.8, Figure 3.

Based on the United Soil Classification (USCS), the tested soil sample is classified as poorly graded SP sand. By direct shear test it is determined that the angle of internal friction is 300.

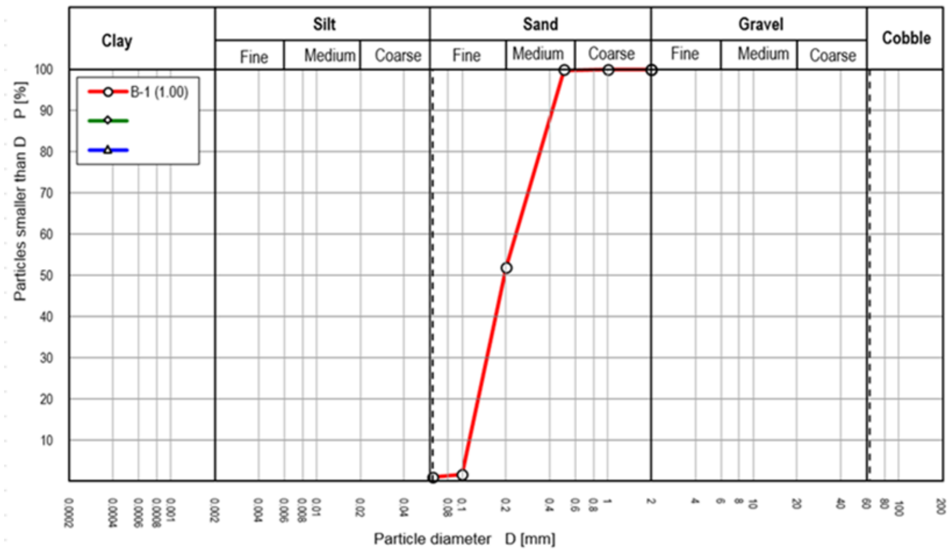


**Fig. 3** The granulometric curve

### 2.2 Models of Capping Beams and Piles

The model of the capping beam across the tops of the piles is composed of a square capping beam. The capping beam is made of steel S 235, plate thickness 10 mm, which is an absolutely rigid body that is not subject to bending under forces occurring in the experiment. 9 mm diameter holes are drilled in the capping beam, arranged depending on the configuration of the piles, through which the pile head passes, at the top of which a thread is incised, in order to tighten the piles with a nut from the upper side of the capping beam and thus achieve a rigid connection between the capping beam and the piles, Figure 4. Piles are made of steel S 235 with a diameter of 12 mm, and for easier and simpler installation, they are composed of three parts. The base of the pile is conical, in order to facilitate the breaking of the piles, while in the upper part of the pile, a so-called adapter is placed, over which the connection between the capping beam and the pile is made. In the adapter, the axial force in the pile head is measured via a miniature force sensor.

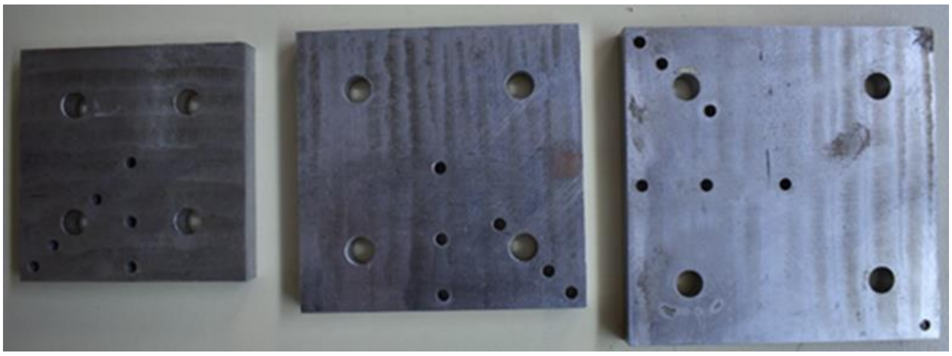

**Fig. 4** Capping beams for group of 2x2 piles

### 2.3 Measuring Instruments and Equipment

#### *2.3.1 Test box*

Model testing was performed in specially designed test boxes. The box is made of steel L profiles and the dimensions of the box are 75x75x100 cm. In the corners of the mobile platform, four pillars of L profiles, which are interconnected by L profiles 35x35x2 mm, every 25 cm by the height of the pillars, are welded. They form a stable structure with prevented lateral deformations of the box walls. The inside of the box is coated with 3 mm thick Plexiglas, to make it easier to determine the height of the filled sand, as well as to eliminate friction between the sand and the walls of the box, as Mosa and others have observed in their experiments [25].

#### *2.3.2 Measuring instruments*

A data logger with one parallel analog board and eight serial analog boards is used to collect data from measuring instruments. On the parallel board, there is a digital-analog switch that generates an excitation signal for Winston measuring bridges. There is also an eight-channel analog-to-digital converter on the parallel board. Six channels are used on the parallel board, while signals from serial analog boards are fed to the remaining two channels. Serial boards have eight analog inputs, with a total of 64 channels.

*2.3.3 Digital scrolling scale*

To monitor the movement of the capping beam due to load, digital verniers with an accuracy 1/1,000 are used. Three verniers of model 601/SA, with a measuring length of 150 mm, are attached to a special frame construction over flexible magnetic stand.

*2.3.4 Force Probe (a probe that measures the vertical force acting on the capping beam)*

To determine the vertical force acting on the capping beam, a force probe with a measuring capacity of 350 kg is used, with measurement error of 0.2%, Figure 5. Force probe is used to measure static and dynamic forces. Probe calibration was done before use in the experimental analysis. The probe was calibrated to the pressure force by placing weights on the probe and thus its response to increasing load was measured. The basic element of the probe is the wall of the probe which is elastically deformed after the action of force. Four measuring tapes connected to the full Winston bridge, are placed inside the probe.

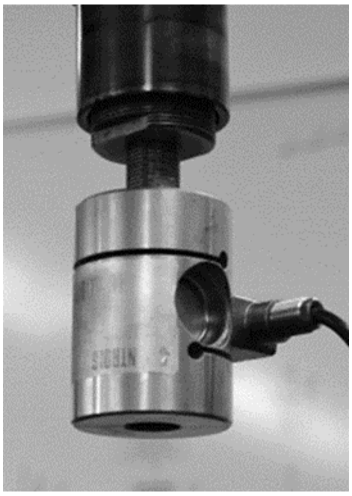

**Fig. 5** Force probe with a measuring capacity of 350 kg

*2.3.5 Sensor for measuring the force in the pile*

A miniature force sensor, with a total measuring capacity of 30 kg, was used to measure the force in the pile The diameter of the sensor is Ø 12 mm. and it has connection necks with notched threads M6. Four measuring tapes, connected to the full Winston bridge, are placed in the sensor. Sensors are placed under the capping beam, in place of the connec-tion adapter. Calibration was performed in the measuring range of the sensor, i.e. from 0 N to 300 N, where the load was gradually increased and maintained for a certain time in-terval, in order to more clearly establish the step of changing the response with increasing load.

*2.3.6 Spreader*

For the purpose of testing the capping beams across the tops of the piles, grounded in loose sand, a self-propelled spreader, 70 cm wide, was made to fill the boxes with sand, in the form of rain from sand, Figure 6.

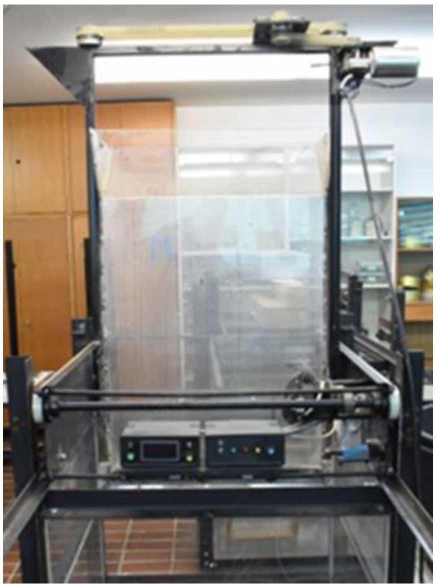

**Fig. 6** Spreader

The spreader has two control panels through which the machine is controlled. One control panel serves to control the movement of the support brace within the box, with a programmer for adjusting the speed of movement. The second control panel controls the support brace box, adjusting the direction of movement of the box in the z-direction, as well as the speed of movement of the box.

**2.4 Examination procedure**

Before testing, the test box is filled with sand by means of a spreader, pouring sand in the form of sand rain at a height of 10 cm, so that the sand remains loose after filling the box.

2. The filled sandbox is placed under the previously installed test frame on which the engine with the mounted hydraulic piston is mounted. A force probe, that registers the vertical force on the system when pressing a group of piles into the sand, is mounted at the end of the piston.

3. The pre-assembled configuration of the capping beams across the tops of the piles is mounted on the force probe and the measuring equipment is connected to the measuring instrument.

4. Before pressing the capping beam across the tops of the piles into the sand, spacers are placed between the piles at certain heights, ensuring that the piles remain vertical when pressed and do not be skewed.

5. After the spacers are installed, the measuring instrument is started and it is checked whether all measuring equipment gives responses. The piles are pressed into the sand at a speed of 10.5 cm/min, until the capping beam reaches the height of 10 mm above the sand.

6. When the capping beam reaches the height of 10 mm above the surface of the sand, the pressing speed is reduced to 1 mm/min and the pressing continues until the ground breaks, or until the capping beam is pressed into the sand to a depth of 0.1B, where B is the width of the beam.

## 3. Results and Discussion

### 3.1 Capping beam without the piles

Load- bearing curves for capping beams without the piles, in the case of capping beams pressing to a depth of 0,1B, where B is the capping beam width, for capping beam dimensions 72x72x10 mm, 84x84x10 mm, 96x96x10 mm, are shown in Figure 7.

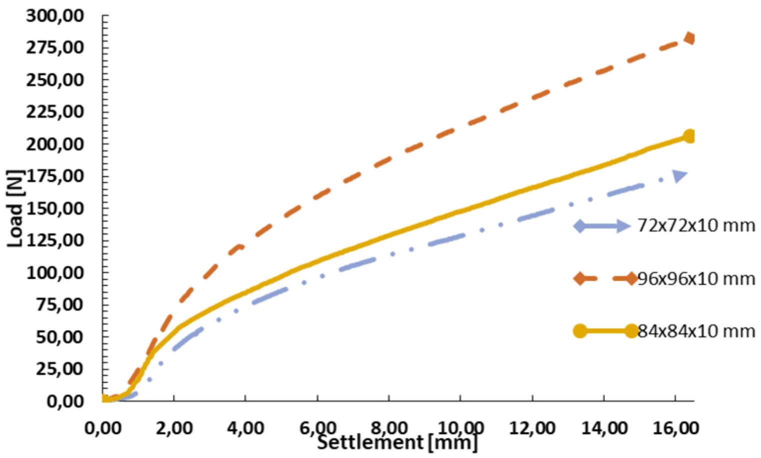


**Fig. 7** Load-bearing curves for capping beams without the piles

The results of the experiment show that capping beams that have a smaller contact surface at the same forces, have higher differential settlements. Such results are expected.

### 3.2 Capping beams across the piles

In the next part, the relationship of load distribution between capping beams and piles during sand pressure, will be analyzed. Figures 8-10 show diagrams force – movement of the capping beams across the tops of the piles for pile length L/d =40, which is often applicable in practice with pile distances of 3d, 4d, 5d. From the diagrams shown, it can be noticed that when the settlement increases, mobility of the capping beam occurs and as the settlement further increases, the part of the force carried by the capping beam, becomes larger. The final settlement criterion is a settlement size of 0.1B, measured from the moment the capping beam touches the sand, where B is the width of the capping beam. The diagram shows the proportion of the load taken by the capping beam. In the group where the piles are at a distance e/d=3, approximately 24% of the total force is taken by the capping beam, for piles at a distance e/d=4, the percentage of force taken over by the capping beam is approximately 40%, and for piles at a distance e/d=5, the capping beam takes up as much as 49% of the force.

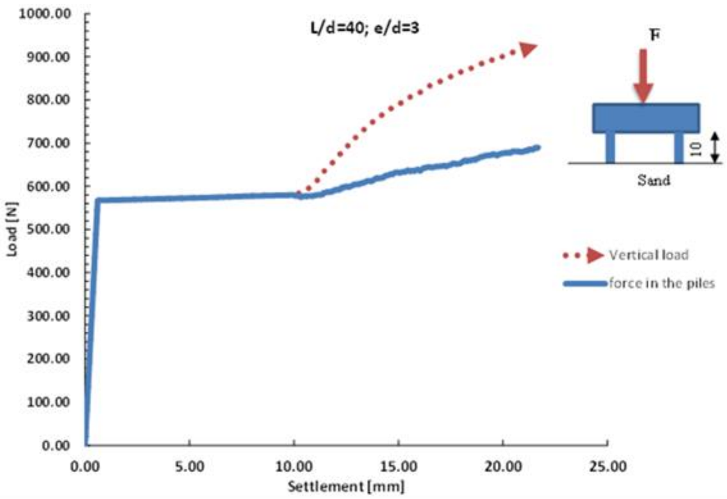


**Fig. 8** Diagram force – movement of the capping beams across the piles L/d=40, e/d=3

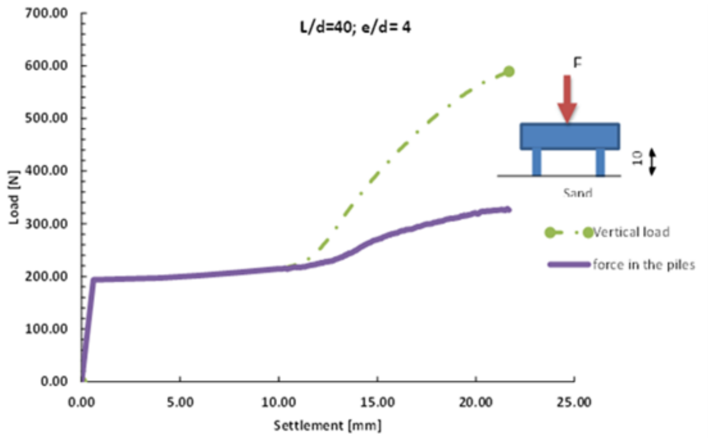


**Fig. 9** Diagram force – movement of the capping beams across the piles L/d=40, e/d=4

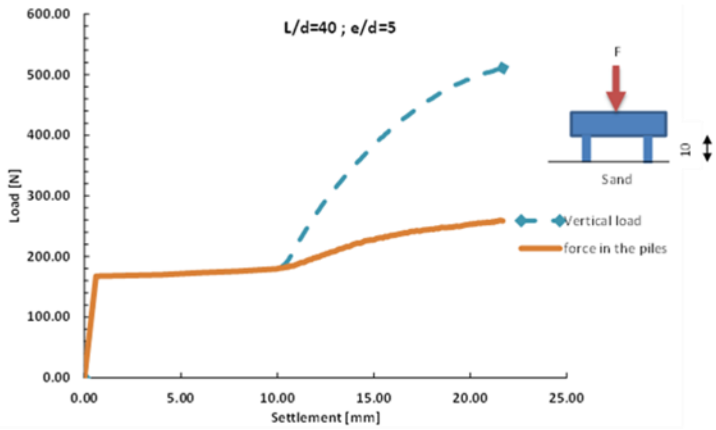


**Fig. 10** Diagram force – movement of the capping beams across the piles L/d=40, e/d=5

Previous diagrams show that when designing these types of foundations, the calculation should not be based on the required number of piles that should accept the entire load, but on the number of piles needed to reduce the settlement to the allowable limits.

### 3.3 Influence of Distance – Group Effect

Within the experiment, the influence of pile spacing on the relationship between load and settlement in a combined system of foundation of capping beams across the tops of the piles, was investigated, as well as the distribution of forces between piles and the capping beam.

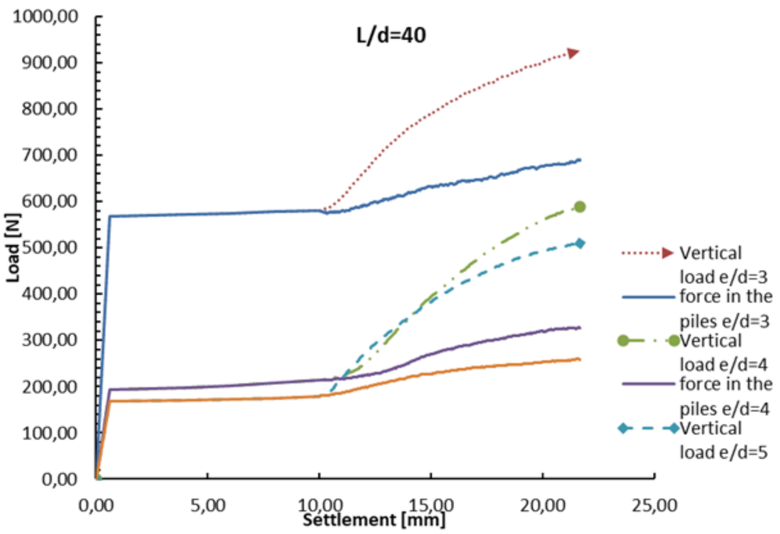


**Fig. 11** Diagram force – movement of the capping beams across the piles L/d=40, e/d=3;4;5

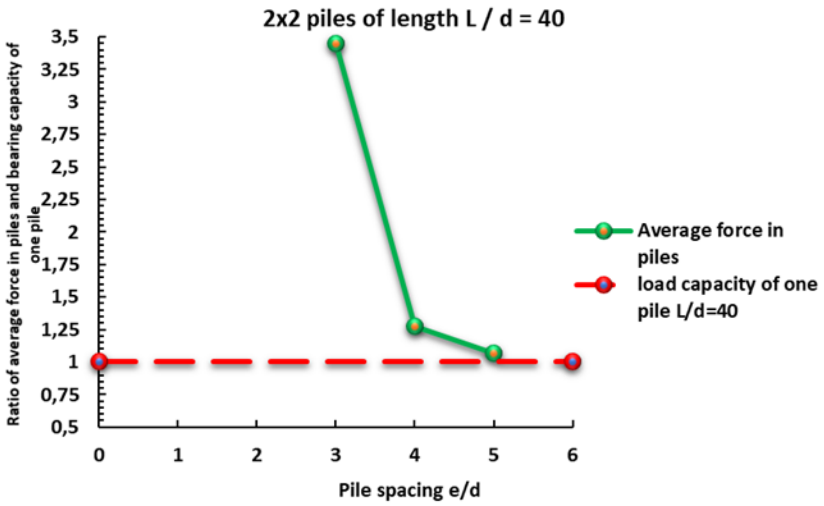


**Fig. 12** The effect of the group of 2x2 piles, for piles length L/d= 40

The diagram in Figure 11 shows that pile spacing has an effect on the relationship between load and settlement in a combined foundation system, so that it is much more pronounced at the spacing e/d=3 and smaller at the spacing e/d=4 and 5. A smaller pile spacing will provide a significant improvement in the performance of the combined system and accordingly, increasing the spacing of the piles leads to an increasing settlement of the foundation. Pile spacing also affects the redistribution of force between the piles and the capping beam. The diagram in Figure 12 shows that the effect of the group is very pronounced in piles that are at a distance of 3d. It can also be concluded that as the spacing increases, the group effect decreases, which is to be expected. At a pile distance of 4d there is a group effect but this effect is much smaller, about 2.8 times. As the spacing of the piles increases to 5d, the group effect slowly begins to be lost and the piles behave as if they were individual. It can be concluded that the final distance between the piles in the group is 5d and that at greater distances the group effect is lost.

## 4. CONCLUSIONS

Based on experimental results, conclusions follow:

1. Capping beams that have smaller contact surface have higher differential settlements at the same forces; increasing the contact surface improves the load-bearing capacity of the capping beam at the same settlements.
2. When pressing a group of piles, immediately after the moment the capping beam touches the sand, a capping beam mobilization occurs and it increases as the settlement increases.
3. It was concluded that in the case of 0.1B capping beam settlement, where B is the width of the capping beam, the part of force taken by the capping beam ZA 3d pile spacing, was approximately 24%. As the distance increased, the part of the force taken by

the capping beam was higher, so at a pile spacing of 4d it was ap-proximately 40%, and at a pile spacing of 5d, the capping beam took approximately 49% of the total force.

4. At 3d pile distances the group effect is very pronounced but as the spacing increases, the group effect decreases. As the final distance to which the piles behave as a group, a distance of 5d is established.

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# EKSPERIMENTALNA ANALIZA PONAŠANJA NAGLAVNIH GREDA NA ŠIPOVIMA U RASTRESITOM PESKU

*Program testiranja je sproveden na 1G modelima naglavnih greda preko vrhova grupe šipova 2Xx2, čija je svrha bila smanjenje sleganja konstrukcije. Program testiranja uključivao je šest eksperimenata, od kojih su tri izvedena na naglavnim gredama bez šipova i tri na naglavnim gredama na vrhovima šipova, sa rastojanjem šipova 3d, 4d i 5d, gde je d prečnik šipa, a dužina šipa 40 d. Rezultati ispitivanja pokazuju da je postojeći konvencionalni pristup projektovanju naglavnih greda preko vrhova šipova, gde je celokupno opterećenje na šipovima, previše konzervativan i iracionalan. Umesto toga, ekonomičnije je primeniti nizak faktor nosivosti za šipove kao reduktore sleganja i maksimizirati korišćenje nosivosti naglavica za nošenje dela spoljašnjeg opterećenja.*

Ključne reči: *pločasti temelj, temelj na šipovima, ploča na šipovima, sleganje, Evrokod*