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SESSION G: CIVIL ENGINEERING

Methodology for measuring pressure at the contact surface between a column footing model and a soil layer limited by a rigid base using Earth pressure cells

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ABSTRACT

The design of all building structures largely depends on the foundation support system, i.e., the relevant actions for structural design depend on soil–structure interaction. This paper describes a methodology for measuring pressures at the contact surface between a column footing model and a soil layer limited by a rigid base using earth pressure cells. The purpose of the research is to assess the reliability of the obtained results representing contact stress distributions between the interacting components under laboratory conditions. The concept of a reduced-scale footing model is presented, along with the procedure for preparing and installing earth pressure cells in the soil, with special emphasis on their position and data acquisition method. The main factors affecting measurement accuracy are also discussed, including soil characteristics, geometric and material properties of the tested footing model. The aim of this paper is to define an experimental procedure for a footing model and a soil layer limited by a rigid base that can serve as a basis for further experimental research and validation of numerical models. The reliability control of the measured contact stresses using earth pressure cells is based on comparison with analytical results. This experimental study examined contact pressures between a footing model and compacted sand using earth pressure cells. Measured pressures deviated significantly from calculated uniform values in the first test (48.3%) due to installation-induced soil disturbance, but improved to an acceptable 9.2% in the third test with proper surface preparation. The load–pressure relationship remained nearly linear across all measurements, consistent with sensor specifications.

KEYWORDS

Foundation, Geomechanics, Contact stresses, Column footing, Earth pressure cells, Reduced-scale footing model, Experimental methodology, Soil layer limited by a rigid base

1. INTRODUCTION

Design of buildings entails the dimensioning of all structural elements based on regulations and codes, whereby the basic design principles relating to stability, durability, and serviceability of the designed structure must be satisfied. This is a demanding engineering process based on known data and data that must be assumed. The dimensioning of structural elements depends on the method of foundation of the building. It is necessary to transfer all loads from the structure to the soil, and in the analysis of the foundation structure–soil interaction [1], as many parameters as possible should be taken so that the behaviour of the adopted model is as close as possible to the actual behaviour of the structure. It is of engineering importance to consider all existing models and apply the best one for the analysed structure and its characteristics.

Foundation of structure depends on many parameters, so prior to design it is necessary to provide all the required data. Data on the physical and mechanical characteristics of the soil are obtained through geotechnical investigation works, which include field and laboratory testing [2]. In addition, it is necessary to investigate existing data for the location where the designed structure will be built. These geotechnical investigation works define the spatial position of soil layers, their thickness and extent, and the depth of the groundwater table. Besides these data, it is necessary to provide data on the

engineering properties of the soil, such as its strength and deformability, as well as all other necessary indicators depending on the purpose and importance of the structure being built. The design of the foundation structure involves determining the dimensions of the foundation based on the bearing capacity of the foundation soil, which is defined by a geomechanical study according to the provisions of Eurocode 7 (EN1997-1:2004), and settlement control in order to satisfy the condition related to the serviceability and functionality of the designed structure.

Due to the influence of the intensity and distribution of contact stresses between the foundation structure and the soil on the dimensioning of structural elements of the building, this paper will present a measurement methodology with special emphasis on the measuring equipment. The aim of the paper is to define the method of placing earth pressure cells intended for measuring soil pressure on a footing model under laboratory conditions. Recommendations will be given regarding the setup of the measuring device and the method of collecting experimental data, based on the manufacturer's instructions, technical characteristics, and observations made during the conducted tests.

2. ANALYSIS OF SOIL-STRUCTURE INTERACTION

For the purpose of analyzing structure-soil interaction, it is first necessary to know the material and geometric characteristics of the interacting elements. When an external load is applied to a body, it induces changes in the internal forces within that body, i.e., the development of stresses, with the system's behavior varying significantly depending on the material properties of the loaded body. In the analysis of foundation structure–soil interaction, the problem is even more pronounced because soil constitutes a heterogeneous and anisotropic material whose mechanical behavior is complex to describe and model [3].

The behavior of soil is most commonly defined by constitutive models that establish the relationship between the stress and strain states. Due to the large variations in the physical and mechanical characteristics of different soil types, there is no single model that can describe all soil types and all forms of their behavior with sufficient accuracy. For this reason, a large number of models of varying complexity have been developed, whereby the choice of model directly affects the results of the foundation–soil–structure interaction analysis [4].

The relationship between stress and strain in soil is predominantly nonlinear. At lower load levels, elastic behavior is dominant, whereas with increasing loads, elasto-plastic deformations occur. The accuracy of the computation depends on the adopted constitutive model and the input parameters describing the soil, which makes their selection one of the key steps in the analysis of foundation–soil interaction.

The simplest model of elastic soil behavior is based on Hooke's law, while the most well-known idealized model of foundation–soil interaction is the Winkler model. The basic assumption of this model is that the soil deflection w (settlement) at any point is directly proportional to the applied load q, whereby this deflection is independent of the loads applied at other points, which can be expressed as (1):

$$q(x,y) = kw(x,y) \tag{1}$$

where: k – is the modulus of subgrade reaction, the unit of which is stress per unit length. In physical terms, the soil is represented by a system of mutually independent springs, due to which deformations occur only in the loaded zone, as shown in Figure 1. Despite the simplifications, the Winkler model still represents the basis of numerous foundation–soil–structure interaction analyses today.

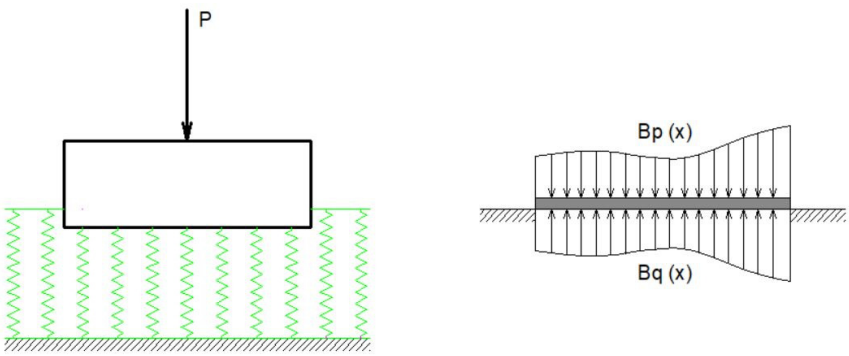

Figure 1: Winkler's soil behavior model

Due to the limitations of elastic models, numerous constitutive models have been developed to describe the nonlinear and elasto-plastic behavior of soil. Among the most significant are the Cam Clay (CC) and Modified Cam Clay (MCC) models, the Soft Soil (SS) model, the Hardening Soil (HS) and Hardening Soil Small (HSS) models, as well as models based on the 'Bubble' and 'Brick' concepts [5]. Contemporary numerical analyses most commonly use these advanced models because they enable a more realistic representation of soil behavior under different load levels and foundation conditions.

Many authors have investigated the distribution of contact stresses depending on the structure and soil type. Based on experimental research, they have established the patterns of distribution and intensity of contact stresses as a function of the applied load [6]. By analyzing the contact between rigid and elastic bodies, it can be observed that the stress distribution over the contact surface is not uniform. Its shape is influenced by a large number of factors, among which the most significant are the geometry and stiffness of the structure, the material characteristics from which it is made, as well as the composition and mechanical properties of the soil onto which the loads are transferred. The dependence of the behavior of the structure–soil system on the stiffness of the foundation and the structure, the shape and dimensions of the contact surface, the depth of foundation, the soil type, the type and eccentricity of loading, as well as other relevant parameters, has been the subject of numerous studies by authors Selvadurai [7], Olson [8], Hrubesova [9], and Dash [10].

In interaction analyses, cohesive and non-cohesive soils are considered. Figure 2 shows characteristic diagrams of contact stresses for different soil types, as well as the idealized stress distribution most commonly adopted in engineering practice. The diagram in Figure 2.a) refers to the case of a rigid foundation resting on cohesive soil, while Figure 2.b) shows the stress distribution for a flexible foundation on non-cohesive soil. Figure 2.c) represents the idealized linear distribution of contact stresses, which is often used in determining the relevant effects for structural dimensioning.

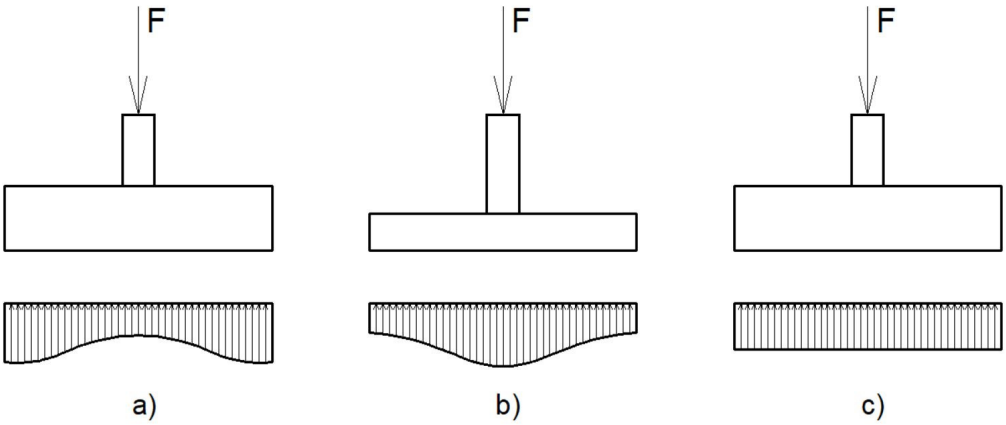

Figure 2: Distribution of contact pressure for different types of soil: a) cohesive soil (φ=0); b) non-cohesive soil (c=0); c) idealization of contact pressure

In addition to soil characteristics, the stiffness of the foundation structure also has a significant influence on the distribution of contact stresses. Figure 3 shows possible stress distributions for different combinations of foundation and soil stiffness. Depending on the intensity of loading and the stiffness ratio of the system, the diagrams may have a saddle-shaped, parabolic, or bell-shaped form.

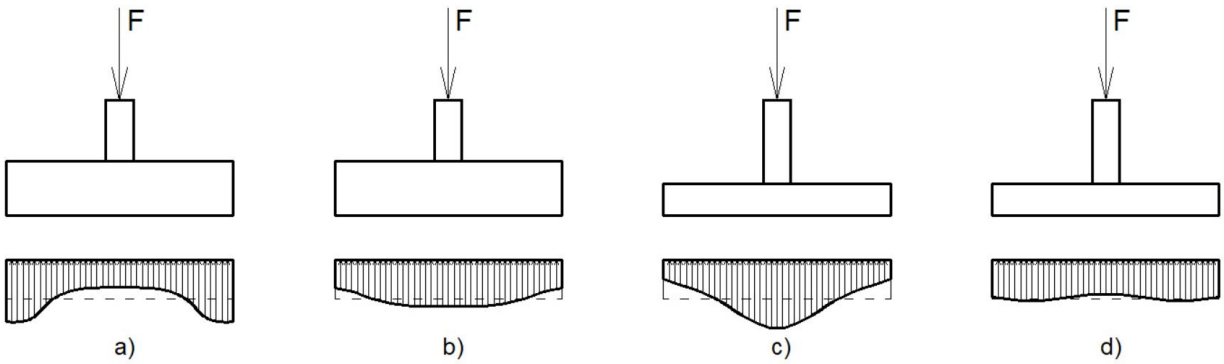

Figure 3: Distribution of contact pressure for different stiffnesses of the footing and soil: a) rigid footing, rigid soil; b) rigid footing, soft soil; c) flexible footing, rigid soil; d) flexible footing, soft soil

The theoretical foundations for the analysis of stress distribution in soil were established by the research of Boussinesq, and were later expanded through numerous experimental and numerical studies [11]. Poulos and Davis, analyzing circular plates of varying stiffness subjected to a concentrated force, showed that the shape of the contact stress diagram depends on the plate stiffness [12]. For an absolutely rigid plate, the distribution has a concave shape, whereas with decreasing stiffness, the maximum stress shifts toward the point of load application, with the stress value increasing as the foundation flexibility increases. Experimental investigations on circular foundations of different stiffness were also conducted by Barnes, and a modified diagram of contact stress distribution compared to Borowicka's research is given in Figure 4 [13]..

Research on strip foundations conducted by Terzaghi has shown a significant influence of soil type on the shape of contact stress diagrams. For cohesive soils, the distribution is predominantly saddle-shaped, while non-cohesive soils exhibit a parabolic distribution. Similar conclusions were confirmed by experimental investigations of rigid rectangular single footings carried out by Boldirev [14]. Further testing of foundations resting on compacted sand and gravel subgrades, conducted by Hegger, Djakov, Bonić and associates [15], showed that contact stresses most often have a parabolic or bell-shaped form.

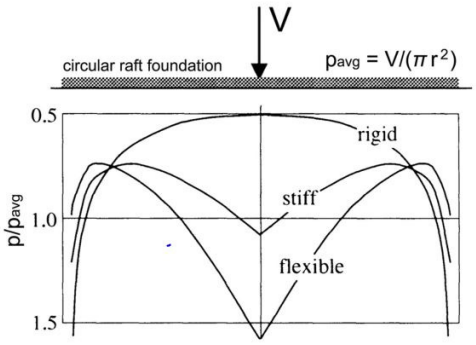

Figure 4: Shapes of contact pressure diagrams (modified from Barnes after Borowicka [13])

3. CONCEPT OF EXPERIMENTAL RESEARCH ON A FOOTING MODEL

3.1. Setup of the Experimental Research

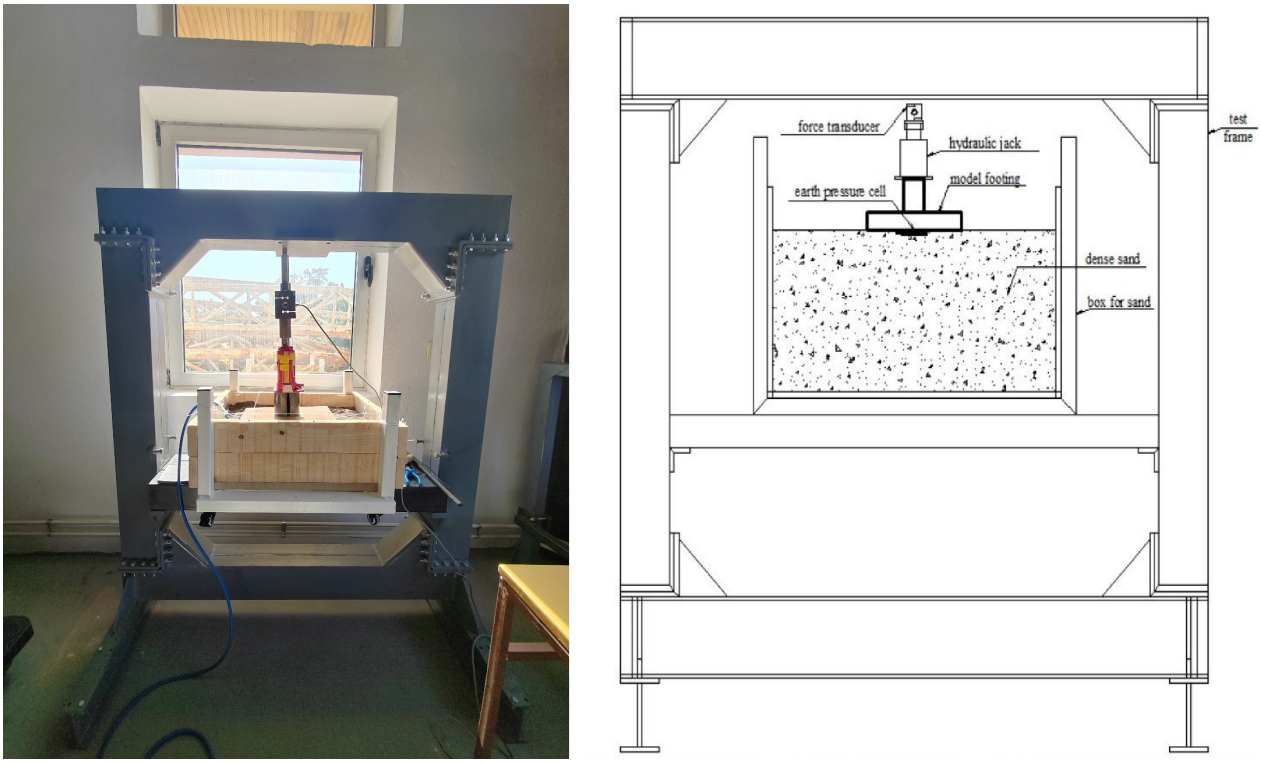

Figure 5: Experimental setup and instrumentation

The setup of experimental research on a footing model under laboratory conditions is shown in Figure 5. On the supports of the testing frame, a soil box is positioned, in which the soil was placed and compacted to a specified density. Subsequently, a earth pressure cell was installed in the soil, with the tested footing model placed above it. The load is applied to the footing model by means of a hydraulic jack, while the applied load is measured using a force transducer (load cell). Based on the measured values of contact stresses at defined time intervals and the applied load, the relationships between these quantities can be established, and thus the soil behavior can be defined.

3.2. Technical Characteristics of the Footing Model and Soil

The experimental research was conducted on a square footing model, as shown in Figure 6. The width (B) and length (B) of the footing model are 30 cm, and the thickness (h) is 6 cm. The model is made of concrete grade C20/25. The load is applied to the contact surface through a column of square cross-section, with side dimensions (b) of 10 cm and height (h1) of 10 cm.

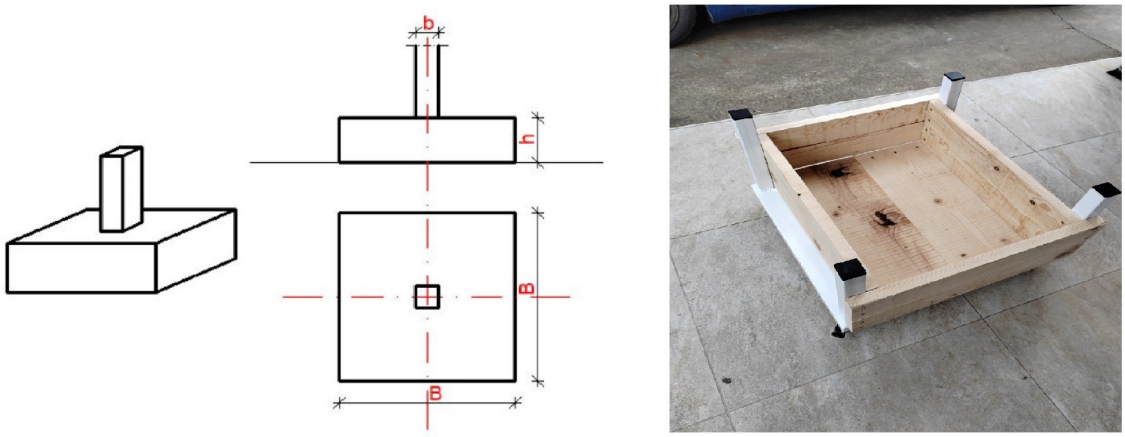

Figure 6: Dimensions of the footing and box for sand

The footing model rests on fine-grained soil – sand with a grain size of up to 2 mm, which was compacted to a specified density prior to testing. The box shown in Figure 6 was used for the experiment, with the sand placed inside and lateral expansion of the soil sample prevented. Since the stress distribution results were compared with the theoretical distribution corresponding to an rigid base, vertical displacement of the base (the bottom of the box) was also prevented in the model [16]. The sand box has a rectangular cross-section with dimensions of 60 × 47.2 cm, and the soil layer thickness is 15 cm, which corresponds to half the width of the footing. The cross-sectional dimensions of the box were determined such that approximately half the width of the footing base was provided on each side between the sidewalls of the box and the footing. For the purposes of this experimental research, the base can be considered incompressible since the vertical displacement of the bottom of the box is prevented.

3.3. Application and Technical Characteristics of Earth Pressure Cells in Structure–Soil Interaction

For measuring the contact pressure between the footing model and the soil layer, earth pressure cells (Earth Pressure Cells 4930 – EPC) manufactured by ACE Instrument Co., Ltd., shown in Figure 7, were used. These are sensors based on foil strain gauge (FSG) technology, intended for determining total stresses in geotechnical structures and experimental models. The strain gauges are placed on the active side of the cell, which is also the cell membrane, while the other side of the cell is the cover.

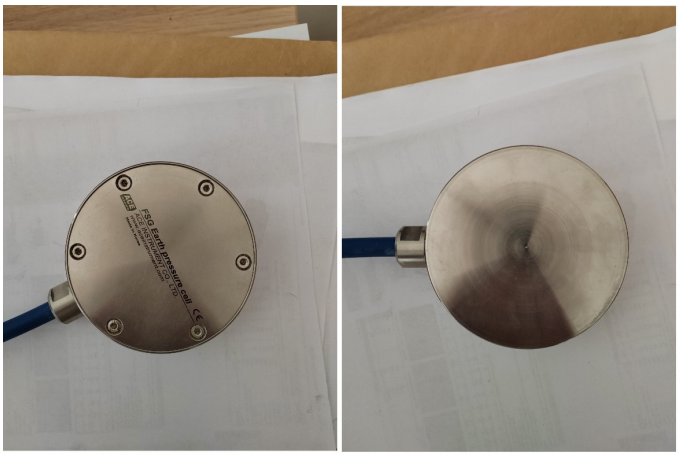

Figure 7: Earth pressure cell ACE Instument 4930, a) cover EPC; b) membrane EPC

The measuring principle is based on the deformation of the sensor's elastic membrane under the action of external pressure. The change in deformation is recorded using strain gauges connected in a Wheatstone bridge, whereby an electrical signal proportional to the applied pressure is generated.

The cells used in this research have an outer diameter of 100 mm and a total thickness of 20 mm. The sensor housing is made of stainless steel with high-quality epoxy protection, which ensures moisture resistance and long-term measurement stability. The sensor has a waterproof construction and is designed for use in demanding field and laboratory conditions.

The characteristics of the used measuring cell are shown in Table 1. The measurement range of the sensor is from 2 to 35 kg/cm², while the declared accuracy is ±0.5 % of the full scale range (FSR). The non-linearity of the sensor does not exceed ±1.0 % FSR, and the allowable overload is 120 % FSR. The output signal of the sensor is 1 mV/V at nominal load, while the nominal electrical resistance of the Wheatstone bridge is 350 Ω.

Table 1: Specification earth pressure cell

Characteristics	Model: 4930
Sensor Element	FSG sensor (foil strain gage)
Range	~23.36 kg/cm^2
Accuracy	±0.5% FSR
Nonlinearity	±1.0% FSR
Over range capacity	120% FSR
Rating output	1 mV/V (1,000x10^{-6})
Resistance	350Ω
Insulation resistance	More than 100 MΩ/500V
Exciting voltage recommended	Less than 5 VDC
Exciting voltage allowable	Less than 10 VDC
Operating temperature	-30~80°C
Water proof	300m H_2O
Weight	1.2kg
Material	Stainless steel, high grade epoxy potting
Signal cable	Ø10mm, 0.5mm^2 x 5C shielded PVC sheath cable

The sensor is powered by a DC voltage of less than 5 V, while the maximum permissible excitation voltage is 10 V. The declared operating temperature range is from −30 °C to +80 °C, which enables application in a wide range of experimental and field conditions.

The pressure cell can be installed in any position, as shown in Figure 8, and in accordance with the manufacturer's recommendations [17]. During the installation of the pressure cell, special attention was paid to achieving uniform contact between the pressure cell, the footing model, and the soil, in order to ensure the most uniform transfer of contact pressure to the active surface of the sensor (the cell membrane) and to reduce the influence of local stress concentrations.

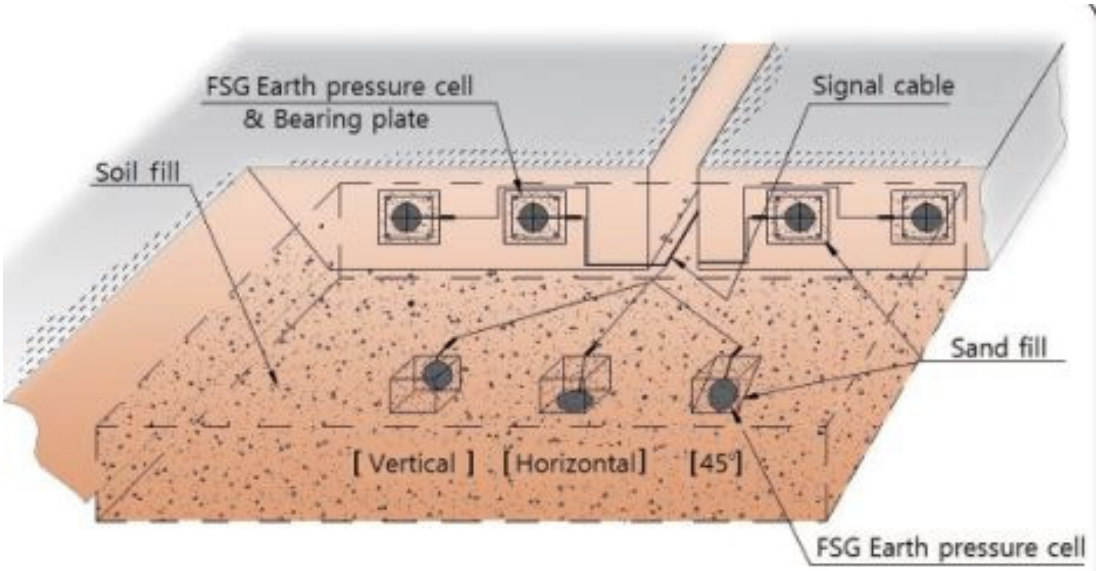

Figure 8: Installation of standard type FSG earth pressure cell

4. EXPERIMENTAL RESULTS AND ANALYSIS

4.1. Experimental Results

The results given in Table 2 were obtained using the measuring equipment specified in Chapter 3 with the given experimental setup. The load was applied using a hydraulic pump, and the load intensity was measured using the HBM RSCC 3C/5t force transducer. The loading results provided the load intensity values over a time interval, while the results obtained from the earth pressure cell defined the pressure on the contact surface between the single footing model and the soil, at the position where the sensor was placed, also over a time interval. Based on these results, the relationship between the applied load and the soil pressure can be established for any moment during the measurement period. Data acquisition was performed using the HBM QuantumX MX840A data acquisition system and Catman Easy data acquisition software. An example of the acquired data from one of the measurements is shown in Figures 9 and 10.

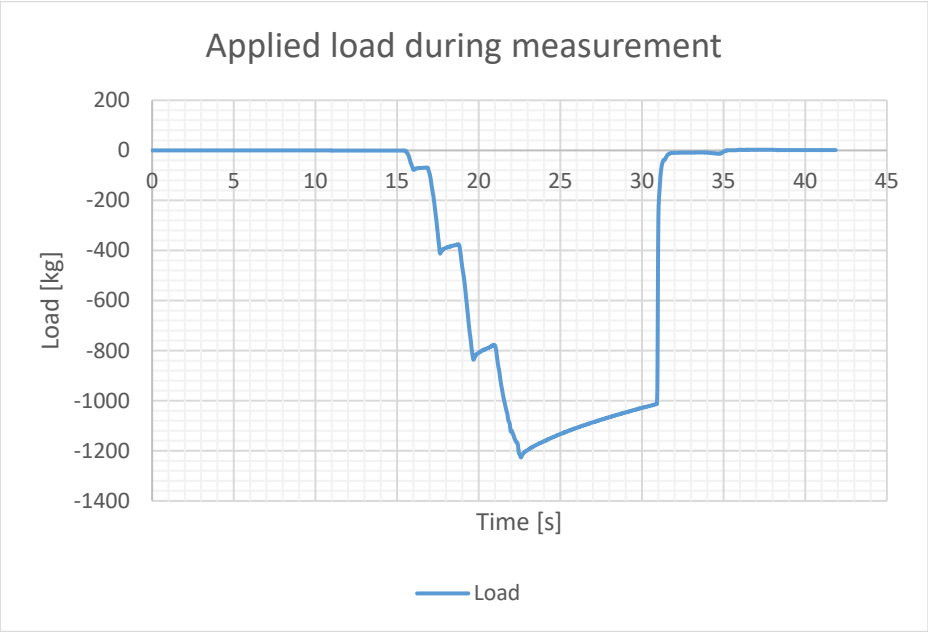

Figure 9: Applied load during measurement

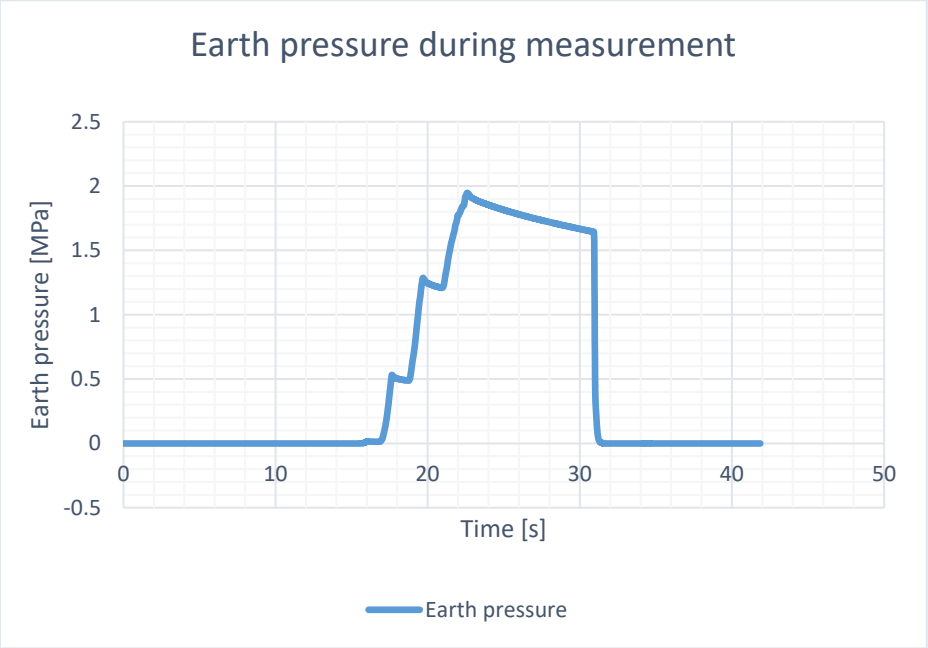

Figure 10: Earth pressure during measurement

The measurement results shown in Table 2 represent the stress values on the contact surface when the cell was embedded in the soil at the center of the footing. Three measurements were performed, in each of which the load was applied in five steps of different intensities. The first applied value was 750 kg, followed by 1250 kg, 500 kg, 1000 kg, and 1500 kg. Prior to embedding the cell into the soil, a 5 mm thick layer of fine-grained sand with a maximum grain diameter of 0.5 mm was placed between the compacted sand and the cell, in order to transfer the reactive load from the soil as evenly as possible to the cell membrane. During the test, the footing model was directly supported on the cell cover, as shown in Figure 11.a). One measurement was also performed with a 5 mm thick rubber layer between the pressure cell cover and the footing model, as shown in Figure 11.b), in which the pressure values on the contact surface were considerably lower than the expected uniformly distributed load values, so these values were not considered in further analysis. Horizontal stresses were also measured by placing the cell at the contact between the sand and the box walls, as shown in Figure 11.c); the measured pressure values amounted to 0.0 MPa.

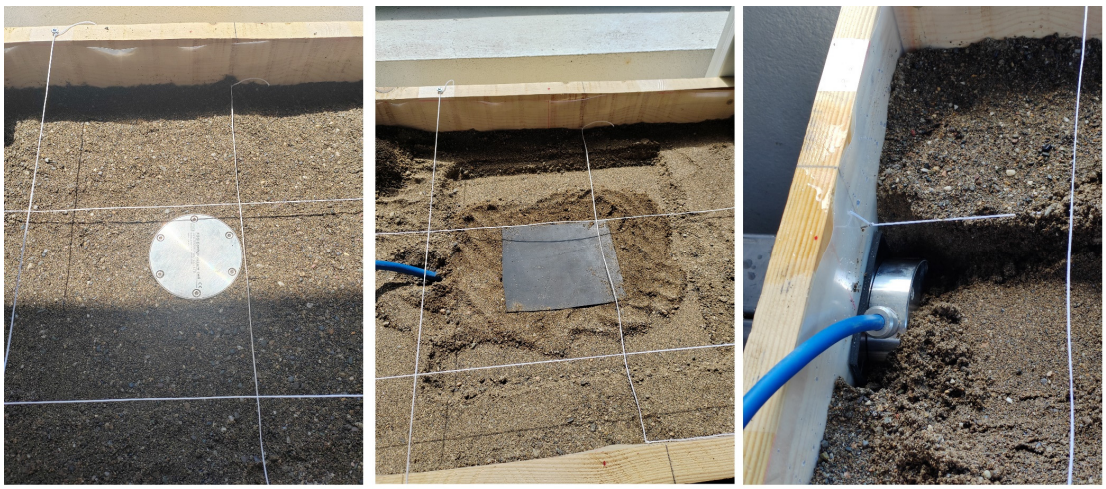

Figure 11: Different earth pressure cell placement configurations

Table 2: Applied loads and measured contact pressures during testing

Measurement ID	Load [kg]	Load [kN]	Measured contact pressures [MPa]	Calculated contact pressures [MPa]	Relative deviation [%]
1.1	526.77	5.17	0.026	0.057	54.7
2.1	769.92	7.55	0.031	0.084	63.1
3.1	1087.81	10.67	0.066	0.119	44.4
4.1	1273.84	12.50	0.071	0.139	48.9
5.1	1638.68	16.08	0.124	0.179	30.6
1.2	552.46	5.42	0.045	0.060	25.3
2.2	744.60	7.30	0.054	0.081	33.4
3.2	1022.94	10.04	0.087	0.112	22.0
4.2	1253.32	12.30	0.106	0.137	22.5
5.2	1591.70	15.61	0.146	0.174	15.8
1.3	531.46	5.21	0.055	0.058	5.0
2.3	775.53	7.61	0.076	0.085	10.2
3.3	1029.69	10.10	0.100	0.112	10.9
4.3	1248.80	12.25	0.122	0.136	10.4
5.3	1505.13	14.77	0.148	0.164	9.8

4.2. Analysis of Results

The results obtained from the testing and the relationship between the results for the first, second, and third measurements are shown in Figures 12, 13, and 14.

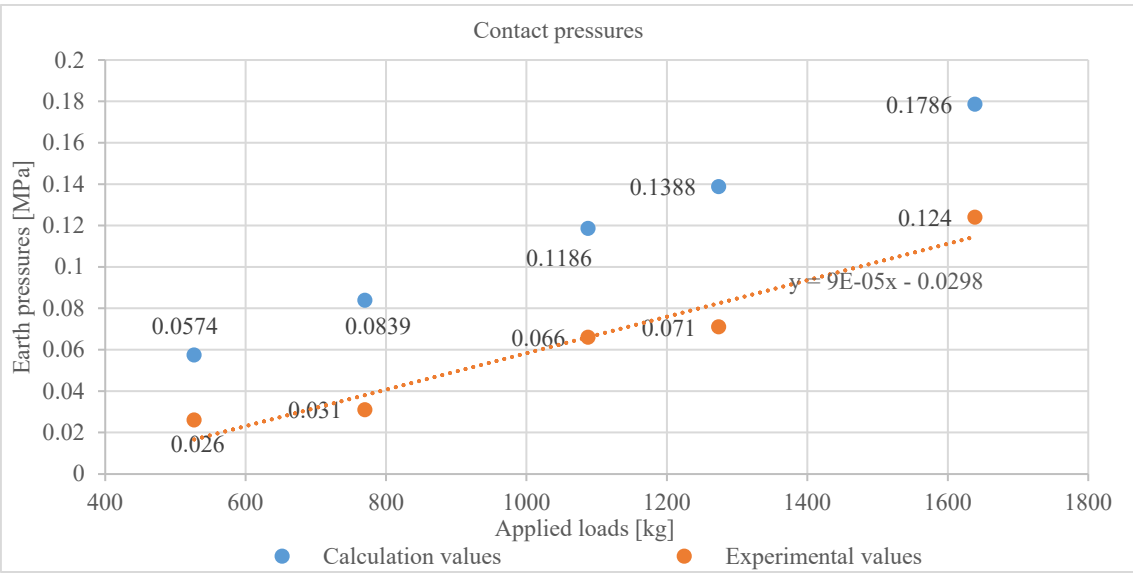

Figure 12: Experimental and calculated contact pressures as a function of applied load – measurement 1

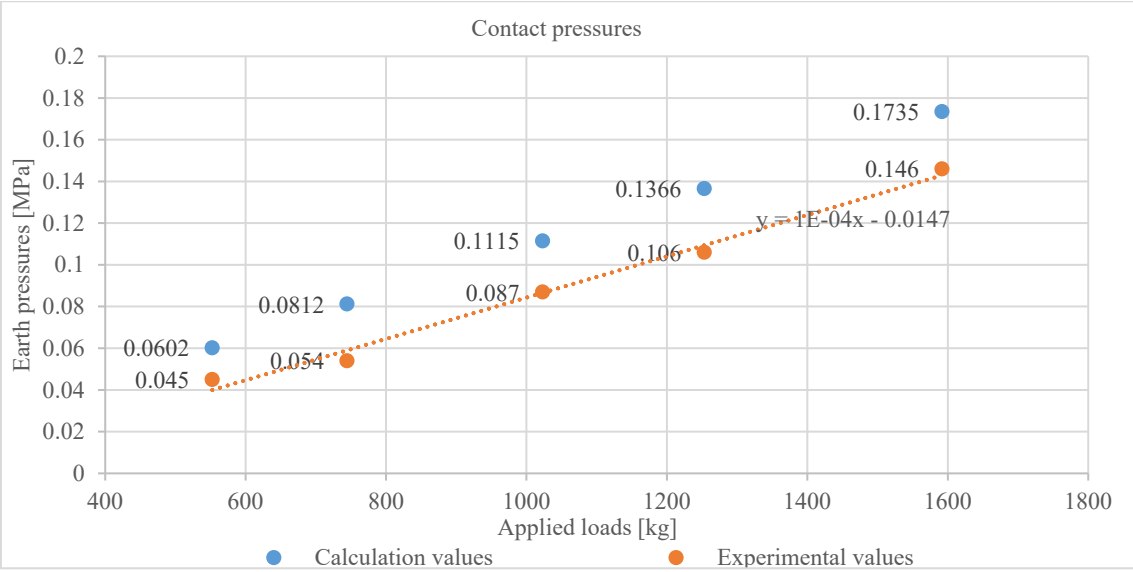

Figure 13: Experimental and calculated contact pressures as a function of applied load – measurement 2

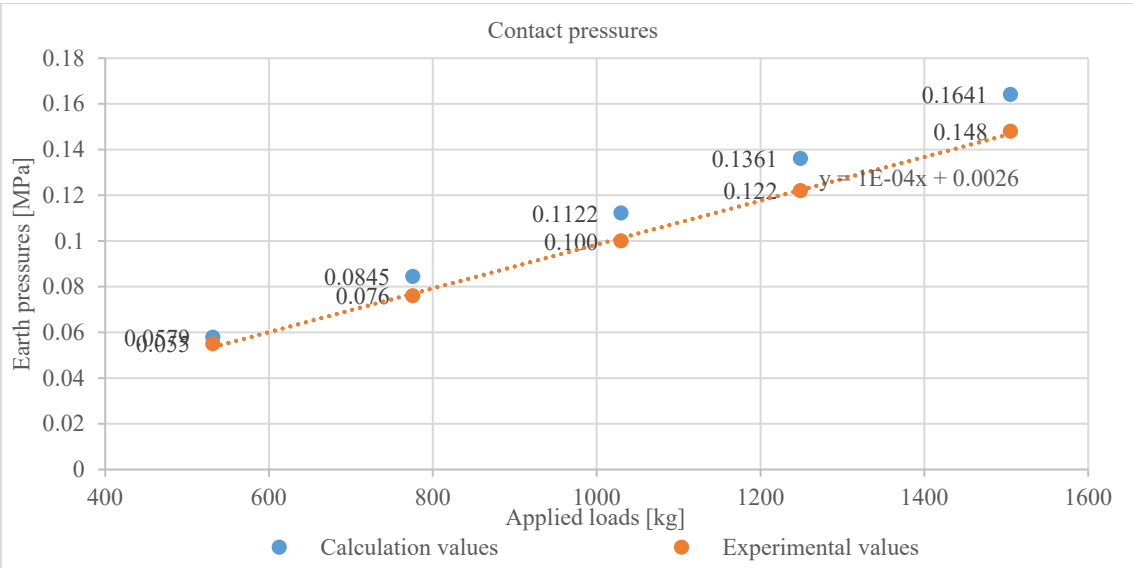

Figure 14: Experimental and calculated contact pressures as a function of applied load – measurement 3

5. CONCLUSION

Based on the presented results obtained through three measurements, it can be concluded that there is a significant deviation between the calculated uniformly distributed contact pressure and the pressure measured during the experimental research. The largest deviation can be observed in the first measurement, with an average deviation of the compared values of 48.3%. This deviation occurred due to the unevenly compacted sand layer around and beneath the cell, because after compacting the sand layer, the compaction was disturbed during the installation of the earth pressure cell. Additionally, it is difficult to estimate the required space for cell installation, so in each test, before the first load application, it happens that the footing model rests either only on the cell or only on the soil around the cell. To avoid such uneven support of the footing model, it is necessary, prior to the start of measurements and after the installation of the pressure cell into the soil, to prepare the contact surface on which the footing model will rest. This preparation entails applying the maximum load to the cell and the surrounding soil using a rigid plate with a contact area not smaller than the area of the footing model, in order to bring the ground level and the cell surface to the same horizontal plane.

This error introduced during the measurement is significantly reduced already in the second measurement, where the average deviation between the compared values is 23.8%; in the third measurement, the average deviation amounts to 9.2%, which is acceptable for the given experimental setup and its geometric characteristics. In all three measurements, the experimental values are lower than the calculated values of the uniformly distributed load on the contact surface.

Regarding the relationship between the contact pressure and the applied load obtained experimentally, in all three measurements, minimal deviations from a linear relationship are observed, which is in accordance with the technical characteristics of the earth pressure cell.

In the process of analyzing the results, the imprecise load application should also be taken into account, which could not be avoided in this experimental setup, so the occurrence of small eccentricities of the applied load was possible. Also, the small thickness of the soil layer should not be neglected, so the difference in the soil layer thickness beneath the cell and beneath the footing model relative to the cell thickness is significant. This influence could be eliminated by conducting research in the field, where there would be no limitations at least regarding the thickness of the tested soil sample.

All presented and analyzed results refer only to the contact pressures at the center of the footing model, so it would be necessary to determine multiple positions of the pressure cells in order to obtain the stress distribution over the contact surface. Due to the small dimensions of the footing model, this was not possible in the present experimental research.

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