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PLATE TESTS OF A SOIL-CEMENT CUSHION

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ABSTRACT. Foundation work in loess with a soil-cement cushion (SCC) is a Bulgarian method, applied in more than one hundred buildings and facilities, which has also been of interest in other countries. According to this method loess is transformed into a two-layer soil base with a stronger upper layer. The modulus of total deformation E_0 (plate modulus) of both layers is necessary for the design and it is determined by plate loading.
The plate tests of SCC conducted so far are distinguished in the following groups: trials in laboratory baths and experimental trenches, tests in experimental sites before commencement of construction and testing SCC of real objects. The E_0 modulus is verified by juxtaposition of calculated and really measured settlements. Recently E_0 is determined on the basis of data from re-loading plate test, thus obtaining in some cases better correspondence between measured and actual settlements.
The report presents analysis and a brief summary of the results of the tests carried out so far and gives data for the recently conducted re-loading plate tests of SCC.

Key words: foundation work, loess, soil-cement cushion, settlement, plate test, plate modulus

ЩАМПОВИ ИЗПИТВАНИЯ НА ЦИМЕНТОПОЧВЕНА ВЪЗГЛАВНИЦА

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РЕЗЮМЕ. Фундирането в льос с циментопочвена възглавница (ЦПВ) е български метод, приложен на повече от сто сгради и съоръжения, към който се проявява интерес и в други страни. По този метод льосовата основа се превръща в двуслойна среда, с горен по-здрав слой и за нейното проектиране е необходим модулът на обща деформация E_0 на двата слоя, който се определя със щампово натоварване.
Извършените досега щампови изпитвания на ЦПВ се разделят на следните групи: изпитвания в лабораторни вани и експериментални корита, изпитвания на опитни участъци преди започване на строителството и изпитвания на реални обекти. Модулът E_0 е проверяван (верифициран) посредством съпоставка на изчислените слягания с действително измерените. Напоследък E_0 при естествени почви се определя по данни от повторно щампово натоварване, при което в някои случаи се получава по-добро съответствие между измерените и действителните слягания.
В доклада след анализ и обобщение на резултатите от досегашните изпитвания се дават данни от извършени напоследък опити с повторно щампово натоварване на ЦПВ.

Ключови думи: фундиране, льос, циментопочвена възгавница, слягане, модул на обща деформация, щампово изпитване

Introduction. State-of-the-art of the problem

The soil-cement cushion (SCC) is a Bulgarian method for foundation in collapsible loess mainly of type I (loess with loaded collapsibility), i.e. practically collapsible after moistening only by additional loading (Author license No 16 276/1971). More than one hundred industrial and residential buildings, including the six power units of the Kozloduy NPP, were built in loess using this method. The application of SCC has been reduced during the last three decades but the cushion is still used even in the foundation of important facilities. In 2014-2015 it was implemented in the construction of the Workshop for processing and deactivation of the materials obtained during the decommissioning of the first four power units of the Kozloduy NPP. The National disposal facility for conditioned short-lived radioactive wastes will be also built on such cushion in loess terrain in the proximity of the Kozloduy NPP.

The design of SCC is accomplished on the base of Guidelines for Foundation of Buildings and Facilities in Collapsible Loess Soils Using a Soil-cement Cushion (1976), in which a fictitious foundation method is used (Fig. 1). Recently software programs are applied for this purpose. The total deformation modulus (plate modulus) E_0, determined by plate loading with a metal stamp, is used as a key parameter in this design. In compliance with BDS 8004-84 E_0 is calculated from the stress-strain dependence after single-time loading.

The equivalent-layer method is used in the calculation of settlement, when the z coordinate is replaced by z_{ekv}, determined by the formula:

$$z_{ekv} = h.\sqrt[2,5]{\frac{E_{0,1}}{E_{0,2}}}\quad,$$

where:

h is cushion thickness, m; $E_{0,1}$ – plate modulus of the cushion, MPa; $E_{0,2}$ – plate modulus of the of loess, MPa.

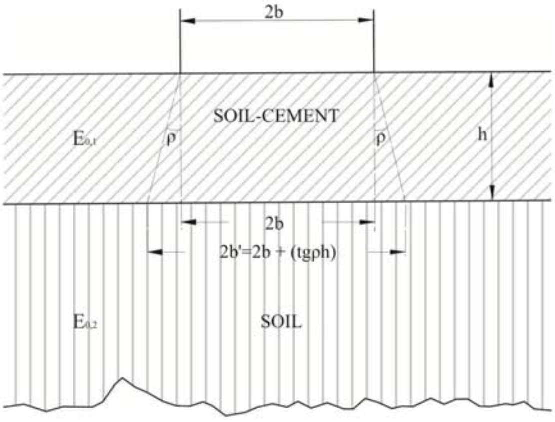

Fig. 1. Principal scheme of the fictitious foundation method

The determination of the plate modulus E_0 of SCC is more difficult compared to that of natural soils for the following reasons:

- SCC makes the loess base two-layered and the settlement of the foundation with greater area is formed not only by the settlement of SCC but also of the natural loess layer beneath the cushion,
- SCC is usually built with increasing cement content in direction from the lower to the upper layers and hence E_0 grows in the same manner,
- At the same time the cushion is built without interruption and the determination of E_0 after thirty days in real conditions is possible only for the uppermost layers,
- The strength and related deformation parameters of soil-cement increase significantly with time, which cannot be practically taken into account.

The main task of the present work is to analyze and summarize the results of the plate tests of SCC conducted so far, to discuss the possibility of using the modulus of the re-loading plate test and to comment some of the above mentioned difficulties in determining E_0 of SCC.

Analysis of previous tests

The plate tests of SCC in Bulgaria were conducted in laboratory baths and in experimental trenches (earth channels) in trial sections before commencement of construction as well as for real objects. The E_0 modulus was verified by juxtaposition of the calculated and the geodetically measured real settlements.

The laboratory tests were realized in a bath with dimensions 0,330x0,335x0,420 m and the loading was applied by a hydraulic press using circular metal plates with diameters d 0,05 m and 0,07 m. A two-layer base was modeled – a lower loess layer (thickness 0,2-0,3 m, *w*=10-15 %, ρ_d=1,37 g/cm^3) and an upper loess-cement layer (thickness h=0,05 m, ρ_d=1,47 g/cm^3, Portland cement quantity q from 5 to 15 %). The deformation modulus and failure mode of the upper layer were determined for different q values (Evstatiev, 1976, Slavov, 1980).

The tests in an experimental trench (earth channel), excavated in natural loess, were realized using seven metal plates with diameters d from 5,64 to 30,07 cm, loaded by a jack (Evstatiev et al., 1979, 1980, Karachorov, 1989). The thickness of the soil-cement (cushion) layer was 10 cm in all tests. Two test series were realized: series A with q=13 % of cement and series B with q=6,3 %. In series B the deformation modulus of the loess base was E_0=25,0 MPa, and of the soil-cement – E_0=200,0 MPa. The unconfined compressive strength of soil-cement was R_c=1,0 MPa. When h/d changed from 1,11 to 0,34 E_0 varied from 122,0 to 49,0 MPa. Two sections are observed in the "loading-settlement" curve s=f (σ) (Fig. 2). The first one corresponds to provisionally elastic behavior – to the boundary values σ_E. The E_0 modulus is determined for this section. The second section is from σ_E to the failure limit σ_{lim} and reflects the elastoplastic behavior of the two-layer base.

The great difference in the stresses provoking one and the same settlement is seen. Even for the biggest plate with an area of 710 cm^2 and loading of 2.10^5 Pa the settlement for the two-layer base in series B is more than five times lower than that of natural loess.

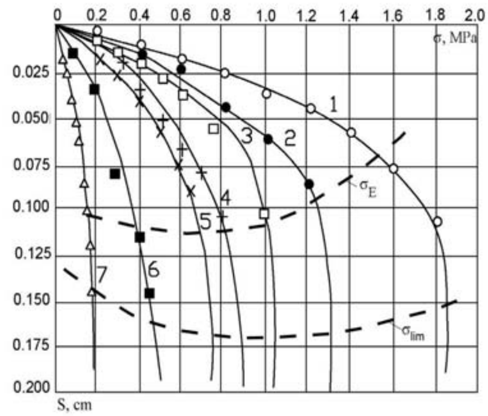

Fig. 2. Stress-deformation relationship for a two-layer base (series B): 1 – plate 64 cm^2; 2 – plate 121 cm^2; 3 – plate 169 cm^2; 4 – plate 256 cm^2; 5 – plate 400 cm^2; 6 – plate 710 cm^2; 7 – loess base, plate 710 cm^2

Although inapplicable for the design, the tests in a laboratory bath and in an earth channel had contributed much to elucidate the strength-deformation behavior of the considered two-layer base. The results obtained for σ_{lim} were compared to the values, calculated using formulas proposed by other authors. It was confirmed that the cushion can substantially increase the load bearing capacity and E_0, provided h/d>0,2 and the ratio between the moduli of soil-cement and loess is $E_{0,1}/E_{0,2}$>5. The important fact that the E_0=f (R_c) relationship is linear has been also established. As will be shown later, this fact is also confirmed by data for SCC of real objects.

Trial sections were built for every bigger SCC application. The greatest number of tests were conducted prior to the Kozloduy NPP construction, where was the major SCC application with a total volume of the cushion about 500 000 m^3.

The thickness of loess at the NPP site of the first four power units is 11,0-12,0 m and of units V and VI – 12-14 m.

The groundwater level for units I – IV, where the plate tests were performed, is at 6,5 – 7,0 m from the surface, the plate modulus below the foundation elevation is E_0=17,0-26,5 MPa, loess is with loaded collapsibility, the collapsibility deformation being up to 1,5-2,0 m under the foundations.

The cushion thickness for the first four units is from 1,5 to 2 m (3,5 m under the reactors). The foundation is mainly in single steps with loading of 0,2-0,4 MPa. The loading under the reactors is up to 0,50-0,60 MPa.

The loess at power units V and VI was removed to the terrace gravels, the four- meter compacted ballast was built on them and two-meter thick SCC was constructed on the ballast layer. The foundation is with a common reinforced concrete plate with dimensions 66,0x66,0 m and loading of 0,45 MPa.

An experimental section was built by Bulgarian Academy of Sciences- BAS and Energoproekt before the commencement of construction of the first power unit, which included the realization of 1-m thick SCC. The modulus of loess underneath was E_0=26,5 MPa. The technological operations and plate tests were conducted in the section. The plate tests proved that loading with a plate with d=0,80 m of the lowermost two layers of SCC with a total thickness h=0,30 m and prepared with q=2,0 % yielded E_0=65,0 MPa, the modulus of the next two layers with a thickness h=0,30 m and q=4,0 % was E_0=85,0 MPa, and the uppermost three layers with h=0,40 m and q=6,0 % showed E_0=110,0 MPa. All layers were compacted to ρ_d=1,74 g/cm^3. Cubes samples with sides of 10 cm were cut from the layers and subjected to unconfined compressive strength tests. The value for the lowermost layers was R_c=0,5 MPa, for the middle ones – R_c=0,8 MPa, and for the top ones – R_c=1,3 MPa. The tests were carried out after 30-day aging – the period after which the plate tests were also conducted (Minkov et al., 1972, 1973, Evstatiev, 1976). In this case, as at other sites, the E_0/R_c relationship was linear (Fig. 3).

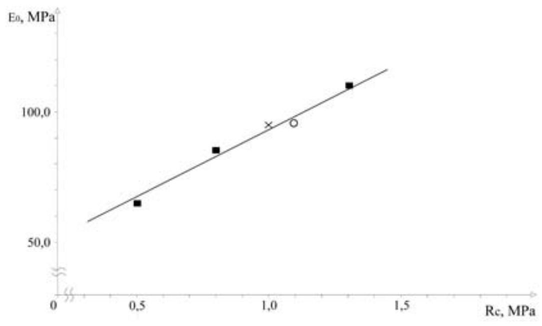

Fig. 3. The E_0=f (R_c) relationship: ■ – for SCC at the experimental site of the Kozloduy NPP, × – for SCC at the metal storehouse in the town of Sindel, ○ – for SCC at the Workshop for processing and deactivation in NPP

Plate tests were conducted under real conditions at many sites but the most representative ones were those at the metal storehouse of the State Reserve in the town of Sindel (Minkov et al., 1979, 1980, Minkov et al., 1981). The storehouse represented a huge hall with an area of about 8000 m^2 and a height of 15 m. The metal elements were stored in the form of pallets with sizes 4x6 m, arranged in strips at a distance of 1,10 m from each other. The load of pallets was from 120 to 500 t. The concrete floor of the storehouse was laid on a 0,5-m thick layer of compacted ballast. The ground base represented clayey loess with loaded collapsibility of type I and a thickness of 4-5 m, with marls lying underneath. The modulus of loess was E_0=20,0 MPa. The concrete covering under the pallets was bended and cracked due to improper exploration and design of the ground base, the settlement reaching up to 40 cm. Stabilization with SCC was selected after discussion of the applicable strengthening methods in the particular case. To this end the storehouse was emptied and a 2,0-m deep excavation was made, where SCC with a thickness between 1,5 and 2,0 m was built. All layers of the cushion were prepared with 5 % of cement. The availability of lifting equipment, heavy sheet metal stacks that were used for loading and the large area of the storehouse allowed the realization of tests with plates of different diameters and with significant loading by a team of BAS and Assoc. Prof. Jelyo Jelev from the Higher Institute of civil engineering and architecture and Fig. 6. Using gauges and soil dynamometers, deformations aside of the plates and the stresses in depth were also measured in addition to the settlements.

The tests were conducted with plates of different diameters. Here, the results with the biggest plate with area F=4,0 m^2 (Fig. 4) and a real pallet with an area F=24,0 m^2 are presented (Fig. 5 and Fig. 6). The plate modulus of the loess base is E_0=20,0 MPa and of SCC – E_0=95,0 MPa.

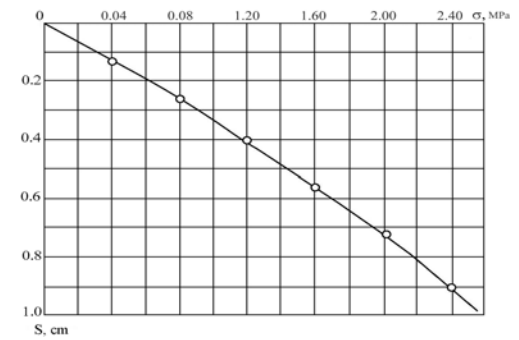

Fig. 4. Results of plate loading of the soil-cement cushion of the metal storehouse of the State Reserve in the town of Sindel (plate area – 4 m^2)

Two tests were carried out with the plate (area of 4 m^2) – for SCC with h=1,5 m and h=2,0 m, yielding for the two-layer base the moduli E_0=48,0 MPa and E_0=55,0 MPa respectively.

Fig. 5. Loading with 24 m^2 metal pallet

With loading to 0,21 MPa, which is in fact the load from a real pallet (Fig. 5), for cushion thickness h=1,5 m, the total settlement measured by gauges placed along the pallet contour is 1,0 cm or 40 times less than the settlement of the loess base that caused the destruction of the concrete pavement.

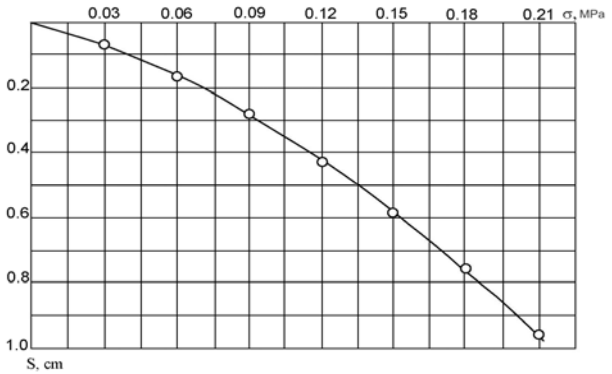

Fig. 6. Results of plate loading of the soil-cement cushion of the metal storehouse of the State Reserve in the town of Sindel (plate area – 24 m²)

After proving by plate and real pallet tests that the ground base was strengthened with a high reserve of safety in terms of bearing capacity and settlement size, the storehouse was subjected to normal operation, continuing for already several decades.

An essential conclusion from methodological viewpoint drawn from all tests considered here, is that the scale effect is strongly reduced and almost disappears for plate diameter d>0,30 m.

Geodetic measurements. The results of the geodetic measurements of buildings and facilities give the possibility to juxtapose the predicted and measured settlements S and S_1 and hence to make conclusions concerning the correct determination of E_0 of the loess base and SCC. For example, the predicted settlements for the TV tower in Ruse according to different methods for a two-layer base are from S=3,73 cm to S=6,85 cm, while the real ones after 30-year measurements are S_1=5,75 cm – Figure 7 (Evstatiev et al., 2008).

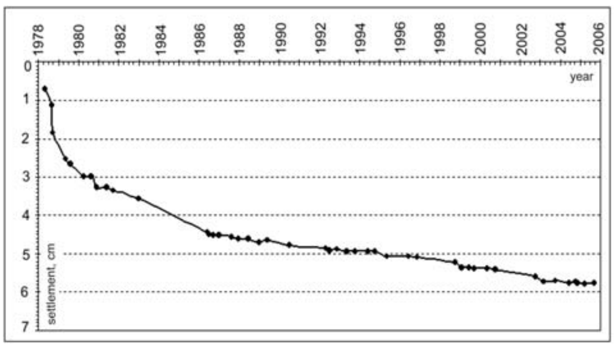

Fig. 7. Averaged graph "time – settlement" of the leveling marks of the TV tower in Ruse

The tower is founded with a common reinforced concrete slab with a diameter d=36,0 m and loading P=0,15 MPa, placed on a soil-cement cushion with a thickness of 4,5 m. The lowermost 1/3 of the SCC layers are with q=2,0 % and E_0=50 MPa, the middle 1/3 – with q=4,0 % and E_0=80,0 MPa, and the top layers – with q=6,0 % and E_0=120,0 MPa (Fig. 8).

The loess under the cushion is compacted using a heavy tamper. The thickness of the compacted layer is 4,0 m thick, with E_0=20,0 MPa. There is natural loess (about 10 m and, E_0=15,0 MPa) under the compacted one, which is non-collapsible for the stresses reaching it.

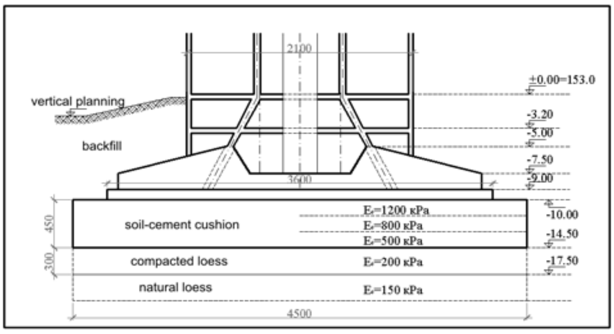

Fig.8. Foundation scheme of the TV tower in Ruse city and plate modulus of the soil base

The TV tower in Ruse is a good example of correspondence between the predicted and realized settlements and for correctly determined E_0 of the layers of the ground base.

The age (time of curing) of SCC exerts great influence on E_0. It is known that R_c of soil-cement increases significantly after prolonged aging (Evstatiev, 1984, Angelova and Evstatiev, 1985, Karastanev, 1988). As stated above, the relationship between E_0 and R_c for SCC is linear, which provides the grounds to expect that similarly to R_c, E_0 will also grow significantly with time. So far we have no experimental data to confirm the expected rise of E_0 with time and until such data are obtained this increase may be considered only qualitatively in the safety assessment of foundations.

Re-loading plate tests

As mentioned before, in compliance with BDS 8004-84 the deformation (plate) modulus E_0 of soil is determined from the stress-settlement curve for one loading with a circular plate (stamp). In the practice of some countries, however, this modulus for natural soils is determined by re-loading (loading-unloading) test. In this way the real conditions are approximated, when during the facility construction certain settlement of the ground base occurs or eventual soil swelling is overcome. The E_0 modulus as determined from the re-loading curve is 2-3 times larger compared to the modulus from the first loading.

The considerations to accept the re-loading test data as reliable for natural soils can hardly be applied for a ground base with strengthened upper part by SCC. However, if in the calculations of settlement the re-loading test modulus is accepted for the natural soil and the modulus defined in the usual way – for SCC, serious discrepancies might appear. This was the case with the design of a facility in the Kozloduy NPP, when the modulus determined according to the standard was used for SCC – E_0=110 MPa, while for the consolidated Pliocene clays lying under the cushion the tripled modulus according to this standard was accepted – E_0=135 MPa. This leads to nonconformity since the unconfined compressive strength of SCC is R_c=1,0 MPa and the same strength for clays is at least 3 times lower.

To get more information on this issue re-loading tests were conducted during the SCC construction of the Workshop for volume reduction and deactivation of equipment of the decommissioned power units of the Kozloduy NPP.

The cushion of the workshop according to the design was 2,0 m thick and was built on loess with a thickness of about 5,0 m, with terrace gravels underneath. Due to loess over-moistening, a compacted ballast layer with a thickness of 0,30 m, reinforced with a geogrid, was placed on excavation bottom. On top of the ballast the SCC was built with a thickness of 1,70 m – the cement quantity for 1,10 m of the cushion being q=5 % and q=7 % for the rest 0,60 m. The average density of all layers was ρ_d=1,71 g/cm^3, and the unconfined compressive strength – R_c=0,96 MPa. The foundation of the building was realized with single and strip foundations, transmitting the load P=0,12 MPa to the cushion. SCC was intended to replace part of the collapsible loess, to reduce the stresses in the remaining loess under it to values smaller than the initial load of collapse and to prevent the access of contaminants to groundwater.

The stamp tests with a circular plate (d=0,30 m) were performed for the first (Fig. 9) and last layer (Fig. 10) of the cushion.

Two tests were conducted for the first layer with q=5 %. The layer was from the experimental section, built 4 months before the plate loading. Similar results were obtained from both parallel tests. The deformation moduli for the first (E_0=40,6 MPa) and second (E_0=64,8 MPa) loading refer to a two-layer base (h/d=0,5) and obviously are strongly influenced by the modulus of natural loess (E_0=12,0 MPa).

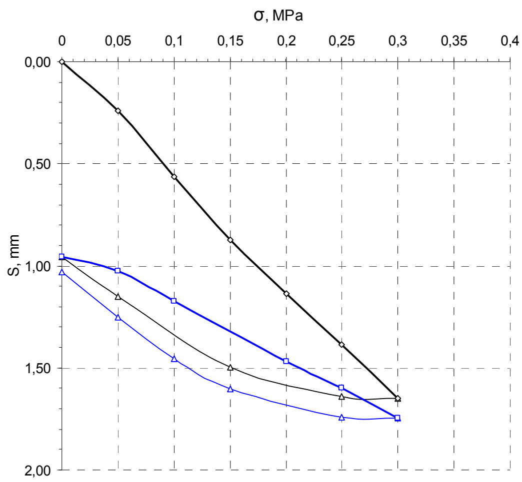

Fig. 9. Loading-settlement curves of the first layer of the soil-cement cushion. E_0=40,6 MPa – first loading and E_0=64,8 MPa – re-loading

Six re-loading tests were conducted for the last layer of the cushion (1 m thick, q=7 % of cement). The higher settlement of natural loess obviously could not exert any effect in these tests due to the large thickness of the cushion and it might be assumed that the obtained results refer to SCC.

The six tests of the first loading yield an average value E_0=95,6 MPa and of the re-loading – E_0=221,5 MPa. On the base of these data it can be concluded that re-loading produces approximately two times higher plate modulus compared to the first loading.

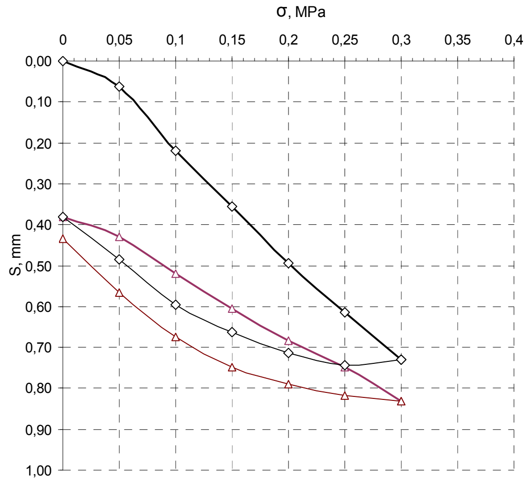

Fig. 10. Loading-settlement curves for the surface of the soil-cement cushion. E_0=88,3 MPa – first loading, E_0=152,8 MPa – re-loading

The difference between E_0 from the first loading and re-loading, when the natural ground base cannot exert any effect is probably due to the discontinuities between the separate layers since poorly compacted mixture with lower cement content may be found along their boundaries. Another reason may be layer exfoliation and surface roughness due to over-compaction. After re-loading these inhomogeneities are removed to a large extent, so that higher modulus is obtained. The load of foundations during the construction of the building will play a similar role and therefore the results of a two-cycle plate test are more realistic in this case.

When the mixture is prepared under stationary conditions the distribution of cement is more uniform compared to in-situ homogenization by a rotor frezno, as is the present case, and it may be expected that the difference between the moduli from both types of loading will be smaller if the layer thickness corresponds to the roller possibilities.

The conclusion can be drawn on the base of the above considerations that data of the re-loading plate test can be used to control the quality of mixing and compacting of the soil-cement layers. If the layers are prepared properly the difference between the first loading and re-loading would be smaller.

Conclusions

The data from the plate tests of the two-layer ground base, consisting of loess and loess-cement cushion, make it possible to draw the following conclusions:

- Depending on the ratio between the cushion thickness and plate diameter h/d the deformation modulus of the ground base E_0 can be increased from 2 to 6 times, reducing several times the settlement and avoiding the hazard of collapse of the loess base of type I.

- The soil-cement cushion can increase the bearing capacity of the two-layer base and its deformation (plate) modulus in the case when h/d>0,2 and $E_{0,1}/E_{0,2}>5$.
- When the amount of cement q is from 2 to 6 % SCC is characterized by E_0=90-110 MPa and unconfined compressive strength Rc=0,9-1,2 MPa.
- It has been established for both small-scale models and real objects that the $E_0=f(R_c)$ relationship is linear.
- The re-loading plate tests of SCC yielded E_0 of about 200 MPa. For the present it is recommended that the re-loading plate modulus should be used when consolidated soils are situated under the cushion.

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