Compaction and Stabilization of Loess in Bulgaria

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M. MINKOV Prof., Bulgarian Academy of Sciences, Geotechnical Laboratory, Sofia, Bulgaria
D. EVSTATIEV Sen. Res. Sci., Bulgarian Academy of Sciences, Geotechnical Laboratory, Sofia
P. DONCHEV Res.Sci., Bulgarian Academy of Sciences, Geotechnical Laboratory, Sofia
G. STEFANOFF Prof., Higher Institute of Civil Engineering, Sofia

SYNOPSIS The present paper reflects in a concise form the Bulgarian experience concerning compaction and stabilization of loess soils in the last 20 years. This experience may be of interest, because in North Bulgaria, on a small area of about 12 000 km^2 all loess varieties, characteristic for the temperate climatic zone are represented in practically significant volumes and areas: loessoidal sands; sandy, typical and clayey loess; loessoidal clays; leached, indurated and consolidated to a different degree loess derivatives. This causes both the profound differences in the qualities of loess soils as a subsoil and the diversity of methods for preliminary preparation of the subsoil by means of compaction and stabilization.

1. TERRAIN CLASSIFICATION

In a terrain patterns design (Minkov, Evstatiev, 1975), convenient primarily for the purposes of geotechnical dividing into districts and mapping, the whole variety of loess subsoils in Bulgaria is included into 3 types and 14 classes. The design allows a pre-orientation with respect to the most expedient way of preliminary preparation of the subsoil by compaction or stabilization. As a basic parameter of the proposed terrain patterns design the total collapse settlement of the loess soil layer at overburden pressure

$$\Delta_c = \sum n_{mp_i} H_i$$

was used. Here n_{mp_i} is the additional relative oedometric settlement caused by flooding the specimen under a vertical loading equal to its overburden pressure "in situ"; H_i is the thickness of a component loess layer i in cm.

In general terms the design includes the following basic classification elements:

1.1. Incollapsible subsoils. They are characterized with a high degree of saturation $S_r > 0{,}70$-$0{,}80$, and due to this, with normal building loads, the whole vertical deformation - under laboratory conditions and "in situ" - goes off as settlement. In part of the cases these are subsoils consisting of naturally consolidated loess soils. With them the dry density is usually high (ρ_d reaches up to 1,70-1,80 g/cm^3), the settlements are small and the bearing capacity-very high (up to 700-800 kPa). In the rest of the cases these are subsoils with low density and a great settlement capacity. Very often they have anthropogenetic origin and are to be found in urban areas, industrial zones and areas under irrigation, where the water content of loess increases gradually without causing any considerable consolidation. At decrease of the water content these subsoils are able to restore-partially or completely-their collapsibility. For that reason they require special attention in geotechnical dividing into regions, mapping and prediction.

1.2. Subsoils prone to collapse under additional loads. Such subsoils are characterized with normal water content (S_r<0,60) and density ($\rho_d \geq 1{,}60$ g/cm^3). They have comparatively small thickness. Under regular building loads part of their vertical deformation goes off as settlement and another as collapse of a different value. Here also belong subsoils, limited in distribution, having a higher density, but with a secondarily greatly decreased water content due to thermic processes or plants with high transpiration capacity. When the moisture regime is normalized, these subsoils become incollapsible.

1.3. Subsoils of intermediate type. This is a special category known by considerable thickness (>5-6 m), a water content increased under the influence of anthropogenetic factors ($S_r \approx 0{,}50$-$0{,}60$), and an usual or low density (ρ_d=1,40-1,50 g/cm^3). At additional (emergency or experimental) wetting throughout the subsoil a total collapse settlement under the overburden pressure up to Δ_c=5 cm is realized. In cases of reduced water content the collapsibility increases and the subsoils are transformed into such of type 1.4.1. The intermediate type subsoils are also to be found in built-up territories or areas under irrigation and are of importance to buildings and other structures with high sensitivity towards irregular vertical deformations. In geotechnical dividing into regions, and particularly in designing of the foundations, the big settlement capacity of subsoils of this type under normal building loads, and their tendency to considerably increase their collapsability with reduction of the water content, should be taken into account.

1.4. Subsoils with Δ_c>5 cm. In Bulgarian building practice they are known as "second type collapsible subsoils" (in contrast to those of type 1.2 which are usually defined as "first type"). They are characterized with 3 vertical zones: upper, non-collapsible zone (h_1) with thickness from 2,5 to 5-6 m; middle, collapsible zone (h_2) with thickness from 2-3 to 25-30 m and lower, non-collapsible zone (h_3) with varying thickness.

The criterion for identification of the second type subsoils, adopted by Bulgarian building standarts, is an integral criterion not considering the values of Δ_c and h_2 and their importance for the various types of structures differentially. For example, for a part of the irrigation structures, where the subsoil is not loaded additionally, settlements up to 20-25 cm do not matter greatly and in many cases can be ignored irrespective of the thickness of h_2. For high structures , however, the size of Δ_c and particularly the thickness of h_2 are of primary importance for the selection of the most effective methods for preliminary preparation of the subsoil. Because of this, an additional differentiation should be made:

1.4.1. Weakly pronounced second type subsoils. Under these fall subsoils with Δ_c ranging from 5 to 25 cm and thicknesses of h_2 up to 10 m, from 10 to 15 m and above 15 m. With these subsoils the value of n_{mp_i} in percentage is to 2-3% at the most, and thus they can be characterized as weakly collapsible. Because of the small value of n_{mp_i} artificial elimination of the collapsability at large depths-for example more than 10 m-is not advisable in most cases and is indispansable only for special structures.

1.4.2. Strongly pronounced second type subsoils. Under these fall subsoils with Δ_c above 25 cm and thicknesses of h_2 to 10 m, from 10 to 15 m and above 15 m. For these subsoils the minimum value of n_{mp_i} is 2-3% and they are characterized as highly collapsible, especially so when h_2 is little. Because of the big value of n_{mp_i}, artificial elimination of collapsibility up to large depths is indespansable and profitable for almost all multi-storeyed buildings and heavy structures. The subdividing of the thicknesses of h_2 for 1.4.1 and 1.4.2 type subsoils is prompted by the differences in the capacities (in respect to the depth) of the various methods for anti-collapse preliminary preparation of the subsoil. This subdividing is arbitrary and is provocativ in character: it has to make the constructors taking concrete decisions, that are always more effective in technical-economical respect than the universal ones.

2. COMPACTION AND STABILIZATION METHODS

The methods and techniques for compaction and stabilization of loess soils in Bulgaria as well as the prospects for their application in civil, industrial and irrigation construction are systematized and described in great detail by Minkov, Evstatiev (1975). In the present paper the possibilities and applications of the methods in close connection with the type and character of the loess subsoil are only briefly summarized.

It is known that the predominant part of methods and techniques for compaction and stabilization of loess soils have been developed in the USSR being applied for a long time very intensive. According to the specific features of Bulgarian loess soils some methods developed in the USSR and accordingly modified as well as some original Bulgarian methods are being applied in Bulgaria now.

The task is to set up a group of methods most suitable for the different classes and types of loess subsoils in Bulgaria. For the moment good results have been obtained for subsoils of categories 1.1, 1.2, 1.3 and 1.4.1 and only partially for subsoils of 1.4.2 (especially at thickness h_2>10 m). It is interesting to note that the maximum measured thickness of loess soils in North Bulgaria is 102 m and that a thickness of h_2 within the range of 25-30 m is a common phenomenon for loess plateaus and high loess terraces.

2.1. Compaction methods for loess soils. With these methods an improvement of the strength-deformability indices is achieved by decrease of the volume of the pores and the distance between the particles of the mineral skeleton of the soil. Several methods for compaction of loess soils using mechanical energy are applied in Bulgaria.

2.1.1. Compaction with a heavy tamper. This is a Soviet method introduced in Bulgaria by the Research Institute of Building. In the last 15 years it has found a wide application in civil and industrial structure, and on a smaller scale as well for irrigation structures on loess soils. The blow energy of 2,5-3,0 tons heavy tamper of reinforced concrete falling freely from a hight of 5-8 m is used. The subsoil is compacted up to a depth of 1,5-1,7 m and the dry density ρ_d reaches 1.80-1,90 g/cm^3 in the upper and 1,55-1,60 g/cm^3 in the lower part of the compacted layer.

Due to the small thickness of the compacted layer the method is recommended for single and strip foundations with a small active zone and only exceptionally for foundation slabs,when the highly collapsible layer is of a small thickness. The effectiveness of the method is influenced decisively by the natural water content of the compacted layer (Minkov et al, 1980).

In this traditional variant the method is most effective for subsoils of categories 1.2 and 1.3 because their natural water content coincides with or is close to the optimal one, at which the depth-effect of the compaction is maximum. For subsoils of category 1.1 its successful application is impossible due to the high value of S_r, and for those of 1.4 - because of the great thickness of h_2. In the latter case it is applied as an exception when h_2 is 2-3 m and coincides with the active zone of the foundations.

In the last 2-3 years a new variant with 4-7 tons heavy tampers of different compaction surface shapes has been experimented and introduced by the Geotechnical Laboratory of the Bulgarian Academy of Sciences (Minkov et al, 1975). When falling from a hight of 7-10 m a compaction to a depth of 2,70-3,20 m is realized. Thus the areas of application of the method for subsoils of the categories 1.2, 1.3 and 1.4 were considerably widened. The experimentation of compaction of collapsible loess soils with 15 tons tampers with a compaction effect to a depth of 5-6 m is under way; the compaction effect guarantees the absolute workability of the method for subsoils of categories 1.4.1 and 1.4.2 with thickness of h_2 to 10 m.

Compaction with heavy tampers, irrespective of their weight, cannot be applied or is difficult in the presence of sensitive buildings in immediate vacinity of the compacted site and also at high values of S_r.

2.1.2. Hydro-compaction and hydro-compaction combined with deep explosions. Hydro-compaction is the oldest method for elimination of collapsibility for thick "second type" subsoils. With it the saturation of h_2 and the influence of the overburden pressure are used (Mavlianov, Karpov, 1958). It is used in many countries-mainly in the USSR and the United States-primarily in the construction of irrigation canals. Due to the slower realization of the collapse settlements and the smaller value of n_{mp_i} of Bulgarian loess soils, compared for example with the loess soils of Central Asia, the method could not find wide application in our country. It is used with the construction of water-levelling beds and canals for additional consolidation of subsoils of category 1.4.2 with thickness $h > 10$ m, where the effect is greatest and can be realized within a comparatively short period of time (for example 5-6 months).

The method proposed by Litvinov (1969) which combines deep moistening with the dynamic effect of directed underground explosions, turned out to be very suitable for Bulgarian loess soils. The method is adapted to Bulgarian conditions, and improved techniquely by the Geotechnical Laboratory. It has been used for compaction of the subsoils of several 16-storeyed residential blocks in Russe (Donchev, 1980). The method has been used at the foundation work of tower buildings on loess and this is done for the first time in the world. The process of compaction takes practically only a moment (from 50 to 80% of the subsidence is realized within minutes after the explosion) and the total collapse is from 2 to 10 times larger than at the regular hydro-compaction. Moreover, apart from subsoils of type 1.4, the effect is surprisingly good at such of categories 1.3, 1.2 and even 1.1 when n_{mp_i} and the thickness of the collapsible layer are great. That widens extensively the possibilities of the method and makes it applicable in cases where the regular hydro-compaction is absolutely inapplicable and ineffective. It should be noted that the scepticism in respect to its effectiveness, expressed by some specialists, is not warrented. For the time being it is not only effective, but the only possible method for compaction of bases of category 1.4.2 with thickness of the collapsible zone more than 15 m and up to 20-30 m.

On a small scale and with a smaller compaction effect another variant of compaction by moistening and explosions, when the blasts were on the surface of the layer compacted, was also used in Bulgaria.

2.1.3. Compaction with short concrete pyramidal piles. This Soviet method was adapted and introduced in Bulgaria by the Research Institute of building while doing foundation work of residential and industrial buildings with single and strip foundations with a limited active zone. Its using was effective for subsoils of category 1.1, when the settlement capacity is big and the bearing capacity small; of category 1.2 in all cases; of category 1.3, when the toes of the piles or the compacted body under them reach an incollapsible layer (the piles are floating and the bearing capacity is due primarily to the compaction effect of the pile sheaf under the foundation); of category 1.4, when h_2 has a thickness of 2-3 m and the active zone coincides with the collapsible one in place and thickness. A considerable advantage of the method is the industrialized production of the piles, although there is a considerable expenditure of cement and steel. At increased density of the soil ($\rho_d > 1,50$ g/cm^3) or a low degree of water saturation ($S_r < 0,30$) the compaction effect and the productivity of driving-in are small and the method is ineffective.

2.2. Stabilization methods for loess soils. With these methods the improvement of the strength and the deformability of the subsoil is achieved by increasing the cohesion due to artificially created interparticle bonds of various nature. Several methods for surface and deep stabilization of loess soils are applied in Bulgaria.

2.2.1. Mono-solution silication. This is a method widely used in different variants (gas silication included) in the USSR. In Bulgaria it was introduced by the Higher Institute of Architecture and Civil Engineering. The method was used for stabilisation of the subsoils of monumental buildings affected by collapse settlements as the church "Holy Trinity" in Svishtov, the Theatre building in Russe (Venkov, 1966), and also for the foundation of a heavily loaded storehouse building. Water-glass with a specific density of $\rho_s = 1.13-1.15$ g/cm^3 (concentration of 15-16%) was used. It was injected under pressure up to 3 atm. The stabilized columns had a diameter of 0,40-0,50 m and the uni-axial compressive strength of the silicated loess was up to 400-500 kPa. Due to the increase of the water content and the density during the collapse deformation of the subsoil, the infiltration of the solution is slow and the stabilizing effect is not high enough. Under such conditions (i.e. with subsoils transformed secondarily to category 1.1) the effect should possibly be better with electro-silication, which in Bulgaria has not been yet adopted.

2.2.2. Cement-soil cushions. Foundation work with soil cushions-of ballast, sand or compacted loess soil-has not gained wide popularity in Bulgaria. There are several reported cases where soil cushions have been used-at subsoils of category 1.2. More popular is foundation work with the so-called soil-cement cushion. The latter represents an artificially compacted and stabilized upper layer of the subsoil, used under single and strip foundations and also under foundation slabs. The cushion substitutes a part of the collapsible layer or the layer with big settlement capacity, redistributes the stresses in the underlying non-stabilized loess to a safety-value, increases the bearing capacity of the artificially created two-layered system, protects the subsoil from wetting and creates a more constant temperature and moisture regime in it. As materials for the cushion the following are used: loess soil from the excavation, ash and cinder rubble from electric power stations or a mixture of soil, ash and cinder. As binding substance portlandcement and flying ash from the electric power stations are used. The method has been developed in the Geotechnical Laboratory.

The cement-soil cushion was used in the foundation work of dozens of multi-storeyed buildings (up to 16 floors)-residential and administrative, heavy industrial and communication structures, the buildings and structures of a nuclear power plant included. This method is suitable for subsoils of category 1.1. (when necessary to increase the bearing capacity and to decrease the settlements) and of category 1.2. With bases of categories 1.3 and 1.4 (with small thickness of h_2) the cushion is combined with compaction by heavy tampers, or is realized as a flat body with trapezium or cone-shaped extensions, that reach to an incollapsible layer. After the earthquake of 1977 with centre "Vrancha"-Roumania it was established that a well designed and realized foundation with soil-cement cushions weakened the destructive effect with 0,5 to 1,5 degrees (MSC scale). More details for the method could be found in Minkov, Evstatiev (1975, 1979).

2.2.3. Screens of stabilized soils. Anti-filtration linings of cement-soil or lime-soil with a thickness of 15-20 cm and a protection soil layer are used in the building of water-levelling reservoirs, as substitutes of concrete linings. They have an enough long life (15-20 years), a big anti-filtration effect and are several times more economical than concrete linings. The adaptation and introduction of the method in different variants has been done by the Geotechnical laboratory.

REFERENCES

Donchev, P. (1980). Compaction of loess by saturation and explosion. Coll.Int.Compactage, Paris.

Dingosov, G., Filipoff, F. (1962). Elimination of collapsability of loess soils by mechanical compaction. Stroitelstvo, 5 (in Bulgarian).

Evstatiev, D.,Rumenov, A. (1972). Compaction of collapsible loess soils by means of explosion energy. Hydrotechnika i meliorazii, 7 (in Bulgarian).

Litvinov, I.M. (1969). Deep stabilization and compaction of collapsible soils. Publishing House Budivelnik, Kiev(in Russian).

Mavlianov, G., Karpov, P.M. (1958). Genetic type of collapse properties of loesses and loessoidal soils of "Golodna step". Publ.of Geol.Inst.of Usb.Acad.Sci., 1044,Tashkent (in Russian).

Minkov, M.,Evstatiev, D. (1975). Subsoils,Linings and Screen from stabilized loess soils. Publishing House Technika, Sofia (in Bulgarian).

Minkov, M., Evstatiev, D. (1979). On the Seismic Behaviour of the loess soil foundation. Proc.of the II US National Conference on Earthquake Engineering.

Minkov, M.,Evstatiev, D.,Donchev, P. (1980). Dynamic compaction of loess. Coll.Int.Compactage, Paris.

Wenkov, W. (1966). Stabilization of collapsible loess by silication. Stroitelstvo, 6 (in Bulgarian).