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REMEDIATION APPROACHES FOR LIQUEFACTION SUSCEPTIBLE DUMPS OF FORMER OPENCAST LIGNITE MINES

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ABSTRACT: The spontaneous liquefaction of soils belongs to the most dangerous types of failure in geotechnics. A local liquefaction failure can occur without any previous signs and trigger a harmful mass movement extending to large areas. The most conservative and long-term feasible technical solution for the stabilization of liquefaction susceptible sites extending to large surface areas is their compaction to a necessary and sufficient level with a smooth, fast and economic soil compaction method, combining geotechnical ground exploration, remediation and quality control in one unified technical process. Under unfavourable geotechnical conditions, soil grouting could also be applied as an alternative and very efficient stabilization method.

ПОДХОДИ ПРИ ВЪЗСТАНОВЯВАНЕ НА ПОДАТЛИВИ НА ВТЕЧНЯВАНЕ НАСИПИЩА В СТАРИ ОТКРИТИ ЛИГНИТНИ МИНИ

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РЕЗЮМЕ. Спонтанното втечняване на почви е една от най-опасните аварии в геотехниката. Локално втечняване може да се получи без да има някакви предварителни признаци и да доведе до вредно движение на маси, разпростиращо се на големи площи. Най-консервативното и устойчиво във времето техническо решение за стабилизиране на насипища, податливи на втечняване, е тяхното уплътняване до необходимото и достатъчно ниво с бърз и икономически изгоден метод за уплътняване на почвата, при който се комбинира геотехническото проучване на земните маси, възстановяването и контрола на качеството в един общ технически процес. При неблагоприятни геотехнически условия може да се приложи също тампониране на почваката като алтернативен и много ефикасен стабилизационен метод.

Introduction

The spontaneous liquefaction of soils belongs to the most dangerous types of failure in geotechnics. A local liquefaction failure can occur without any previous signs and trigger a harmful mass movement extending to large areas. To a potential liquefaction failure, certain soil physical and mechanical conditions must simultaneously prevail in the soil:

- special grain size distribution and smooth grain surface (grain texture)
- low density due to high porosity of the soil skeleton
- special orientation of the grains in the soil skeleton (skeleton structure)
- sufficient water saturation in the pores of the soil skeleton
- low effective stresses in the soil in its initial state
- shear strength dominated by friction with very low cohesion
- sufficient disturbance in the effective stress field due to an internal or external excitation (also termed initial)

Neither liquefaction susceptibility nor the danger of a spontaneous liquefaction failure will be reduced over time, as it is the case in other geotechnical applications, where a certain "natural attenuation" leads to slightly increasing safety factors with soil age. The danger for a spontaneous liquefaction failure can prevail over long time periods in a soil body and it can be triggered, when suddenly all geotechnical prerequisites mentioned above are fulfilled at the same time.

An especially difficult geotechnical situation emerges, when loose and liquefaction susceptible, almost water saturated granular soils are situated immediately under the ground surface due to a very high level of the ground water table. The buoyancy forces lead to a very low level of the effective stresses and instabilities can be induced by low energy excitations in soil regions at low depths. Due to the low density at low effective stresses, the resulting stiffness in the soil skeleton is also low. High compaction energy can lead to a significant density change and high deformations on the ground surface.

The elimination of one or more geotechnical prerequisites listed above can result in a potential reduction of the liquefaction susceptibility. Practical experience proves, that the most conservative and long-term feasible technical solution for the stabilization of liquefaction susceptible sites is their compaction. In liquefaction susceptible dumps of former lignite opencast mines, the stabilization of the residual pit slopes should have high priority. The slopes can be stabilized with the technique of "hidden dams", using a local compaction zone reaching to the maximum dump depth and optionally with the more economic technique of "floating dams", using a local compaction zone reaching to a reasonable depth only. Such compacted zones have successfully been used as adequate stabilization solution in numerous geotechnical applications. In the geotechnical design of the required size of the compaction zone, earth static methods are used with the assumption that the force equilibrium must be safely fulfilled, when the soil liquefies on one side of the compacted zone.

In liquefaction susceptible dumps of former opencast lignite mines, instabilities can also occur in regions far from the residual pit slopes, when the water table level reaches very high levels below the ground surface. If the liquefaction susceptible dump materials extend over great surface areas, their stabilization with compacted zones poses a great engineering challenge. At the selection of the adequate ground stabilization method must be considered, that the compaction of the liquefaction susceptible material should be conservative, certainly excluding the option of failure in loose zones that remain in the dump body posing a potential danger of a local liquefaction failure after the ground treatment.

In the selection of potential stabilization methods should be furthermore considered, that if a liquefaction susceptible dump site is already used for a certain economic purpose, large displacements on the ground surface are generally not desirable. If large settlements of the ground surface are provoked, they have to be levelled or filled up with additional replacement soils. If the groundwater table level is also very high, large displacements could also shift the ground surface under water, leading to new wet surfaces or lakes, posing the problem of the stabilization along the new shore slopes.

For the stabilization of liquefaction susceptible dumps of former opencast lignite mines, the optimum solution is the compaction of the soil skeleton. Prescribing the critical density, the pressure dependent density limit, where dilatancy sets in at shear loading, as the compaction goal level, is economically not feasible and would lead to undesired large deformations in the subsoil. The significant reduction of liquefaction susceptibility in the dump material can be reached with a slight, uniform and sufficient density increase over large areas, leading to a satisfactory reduction in volume changes at subsequent shear loading and avoiding a spontaneous liquefaction failure.

The selection of an appropriate ground improvement method is difficult, as the geotechnical information level on the dumps of former lignite opencast mines is usually very low and due to the large surface, a profound geotechnical exploration is too expensive. Those ground improvement methods are clearly in advantage, when the compaction effect can be estimated beforehand and from the observed ground improvement results, the efficiency of the resulting ground compaction and the increased stability of the treated ground can be determined.

Ground remediation methods against liquefaction

In practice, ground improvement with soil compaction is often carried out with dynamic methods, where the compacting energy is introduced through dynamic excitation of the soil with a wave field. Dynamic ground improvement methods can locally induce high density changes. The introduced wave field will also excite other regions of the liquefaction susceptible subsurface, laying further away and outside of the soil stabilization project area. In consequence of the wave field, undesired displacements of the ground surface and potential liquefaction failures can be triggered.

Another significant problem with the application of dynamic ground improvement methods lays in the fact that their action mechanism is not yet well understood in theoretical models of soil dynamics and their quantitative dimensioning proves to be difficult. It is unclear, which compaction effects will result at which distances to the wave field excitation source and where could uncompacted soil regions as potential failure zones remain in the subsoil after treatment. A reduction of the dynamic excitation energy leads to a higher density fluctuation and increasing risk of insufficient stabilization.

For the installation of stabilizing compacted soil zones, such as “hidden dams” and “floating dams”, the method the vibration compaction and explosive compaction have been extensively used. If the groundwater table reaches very high levels below the ground surface in liquefaction susceptible soils, the application of these methods turns out to be highly complicated, as the low effective stresses and high water saturation ratio lead to very high liquefaction mobility in the soil and the introduced wave field can simply trigger a dangerous liquefaction failure.

The vibration compaction method introduces the compaction energy with an excitation unit. The vibration energy can quickly lead to significant build up of excess pore pressures. It is especially dangerous, when the vibration compaction is carried out in an existing, previously compacted zone of the dump of a former opencast mine, such as the work level of spreaders, as the wave field triggered by the vibration energy can propagate to high distances and induce liquefaction failures over large areas.

As an alternative, a “smooth” version of the explosive soil compaction method can be used with small charges at low depths below the water table level. However, the application of the explosive soil compaction proves to be also very problematic to the compaction of liquefaction susceptible soils in many respects. Up to today, engineering methods for the quantitative dimensioning of explosive soil compaction operations are missing. An approximate quantitative estimate of potential compaction effects can be reached with the extrapolation of existing empirical dimensioning rules. But, the method proves to be poorly scalable for the desired densification effects in the depth and in lateral direction.

The explosive compaction is very likely to cause a bumpy surface with a high levelling effort afterwards and with badly controlled and heterogeneous densification effects that are stronger in the vicinity of the explosive charge and weak in great distance. In order to avoid a destabilization due to excess pore pressures, the application of additional drains is highly recommended, leading to a significantly higher ground treatment effort.

Another great difficulty arises from the fact, that the explosive ground improvement has practically no effect in soil layers without full water saturation. In the naturally saturated layer, even a decrease in the density can be expected, as the wave field form the explosion has a lifting effect on the ground surface above the charge, leading to a loosening and cracking of the weak soil layer above the ground water table. If the ground water rises further and saturates the very loose soil layer under the subsoil surface, the local liquefaction susceptibility can even increase.

The quality control in the heterogeneous density field resulting from the explosive soil compaction poses another difficult problem. The surface settlements can be readily used for an estimate of the densification effects in the ground. However, the quantitative measurement of the spatial density distribution in the soil with reasonable effort proves to be a practically unsolvable problem today.

Finally, the non conservative densification of the ground turns out to be the biggest concern with the application of the "smooth" explosive compaction method. Without the possibility for a quantitative densification control, the question for the sufficient level of ground treatment excluding residual risks of failure cannot be satisfactorily answered.

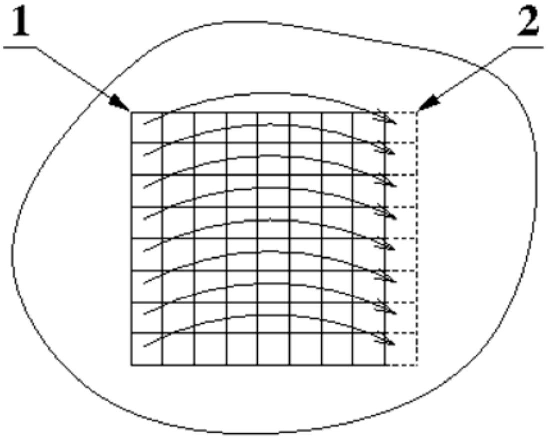

Fig. 1. StaPaC – Technical and geotechnical concept of the static partial compaction

Technical, geotechnical and economic concept of the static partial compaction (StaPaC)

Static compaction methods are based on the concept that the densification effects in the soil emerge from a smooth static loading, avoiding the dynamic excitation of the treated soil. For the stabilization of liquefaction susceptible soils, the Static Partial Compaction (StaPaC) has been developed and recommended by Tamaskovics [Tamaskovics,2011].

The ground improvement with the static partial compaction method (StaPaC) introduces a slight density and gentle structural change in the soil skeleton with a slowly moving quasi-static load on the ground surface and can stabilize liquefaction susceptible dump soils of former opencast lignite mines. The ground improvement method is *partial*, because only a part of the treated soil over the depth will be compacted and only a part of the possible densification spectrum is exerted. The simplicity of the ground improvement method allows for a very economic solution.

The almost trivial technical concept of the static partial compaction (StaPaC) can be observed in a view from above in figure 1. The ground improvement technology consists of a large modular dead load moved piece after piece by a mobile cran. The dead load elements can be advantageously old ship containers filled with a heavy sediment or simply sand. Ideally, iron cubes made from scrap could be also used as long term investment and the bound capital regained after finishing the ground improvement operation. Great advantage of the latter technical and economical option would lay in the more concentrated load and simpler handling of the smaller surface loading units.

The static partial compaction (StaPaC) unifies the geotechnical ground exploration, the ground treatment and the quality control of the ground improvement in one technical process, as it is practically nothing different than a moving test loading on the ground surface. The resulting densification effect to be expected is selective, inducing a higher compaction effect in more loose soil regions.

The static partial compaction (StaPaC) has a great number of advantages in comparison with alternative methods of ground improvement. The loading of the treated soil with a wave field can be completely avoided. Near protected objects that are sensitive to a dynamic excitation, the application of a static loading is the unique alternative.

The soil mechanics process of the static partial compaction (StaPaC) during the ground improvement introduces a large loading and unloading cycle of normal and shear stress. During subsequent loading, due to the pre-load, the improved soil behaves stiffer in the previously introduced stress range. The ground improvement procedure is fully applied over the complete subsoil surface and definitely reaches each soil particle in the ground. Immediately after the soil compaction to a sufficient level, the economic utilization of the subsoil is further possible.

The static partial compaction (StaPaC) has three adjustable technical operation parameters. The geometrical extension of the dead load on the surface influences the depth of soil treatment. The stress level under the dead load determines the compaction impact and stress reversal intensity. The velocity of the surface load movement controls the induced excess pore pressures that provoke a groundwater flow and spatial consolidation process. For the geometrical extension of the dead load on the surface, a minimum size of 20mx20m is recommended, reaching definitively a treatment depth of 20m. The stress level under the dead load can be adjusted to the sensibility of the liquefaction susceptible ground to be improved. From the time dependent settlement of the surface load, the spatial consolidation process and the induced compaction effects can be back calculated with inverse methods of soil mechanics. The measured spatial distribution of the stiffness in the subsoil allows for the estimation of the ground improvement operation quality. With additional pore pressure measurements and auxiliary drainage elements, the spatial consolidation process can be monitored and the overall geotechnical safety of the ground compaction unit can be increased.

The technical applicability of the static partial compaction (StaPaC), some prerequisites must be secured. The ground must be levelled and surface obstacles removed. The ground improvement method advances slowly, but this can be compensated with the number of loading active units.

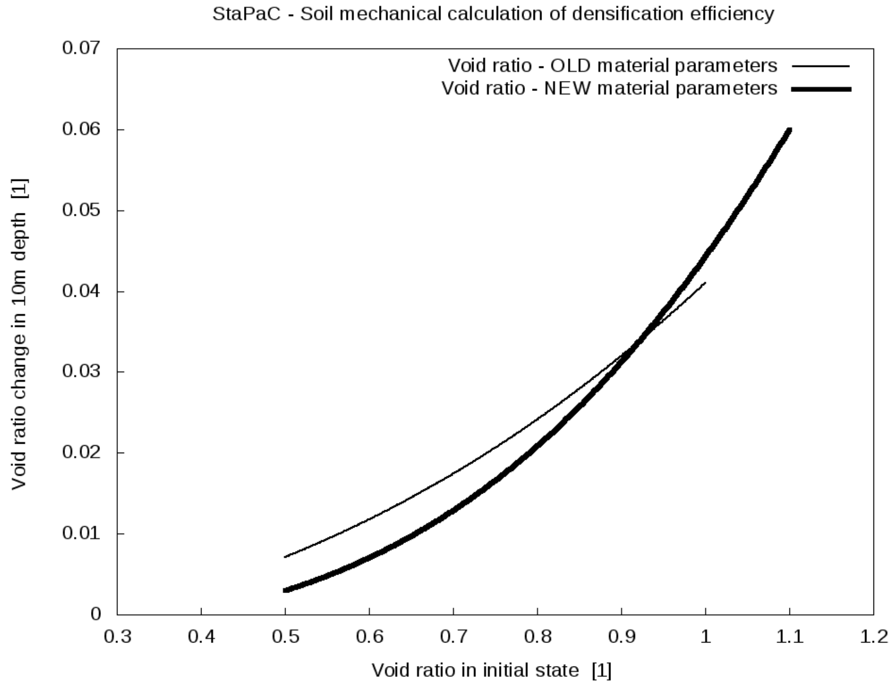

Fig. 2. StaPaC – Void ratio change estimate due to the moving surface load

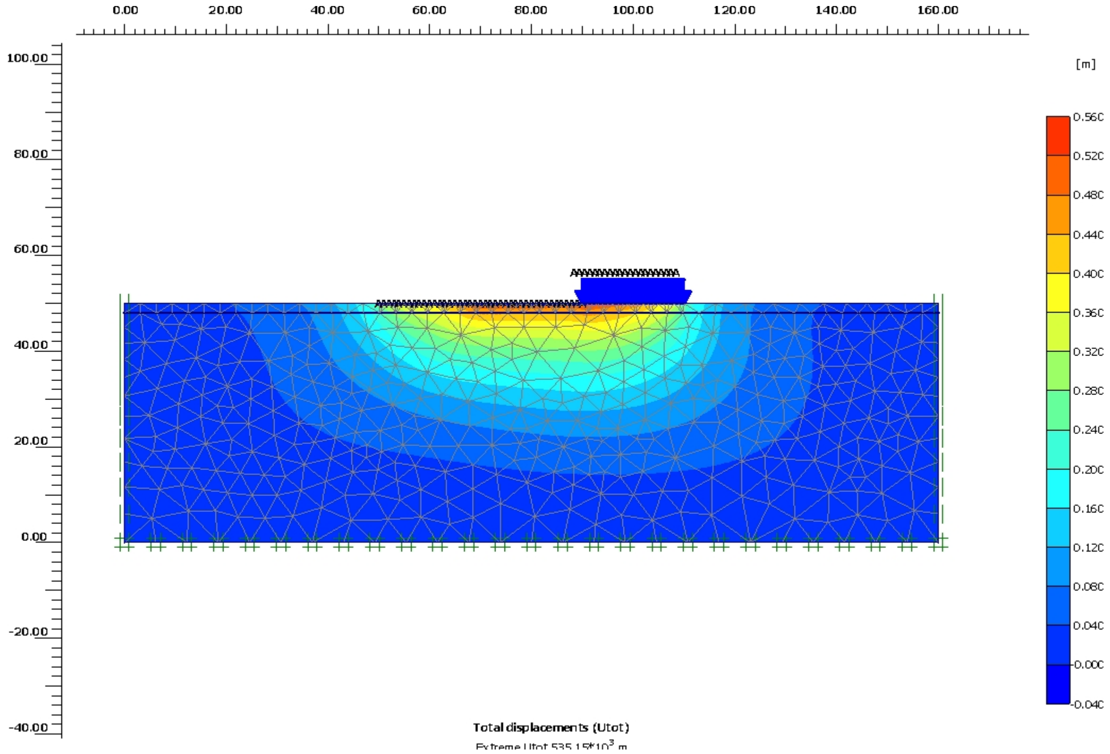

Fig. 3. StaPaC – Quantitative estimation of the compaction effect – Soil displacements predicted with the hypoplastic constitutive equation of von Wolffersdorff

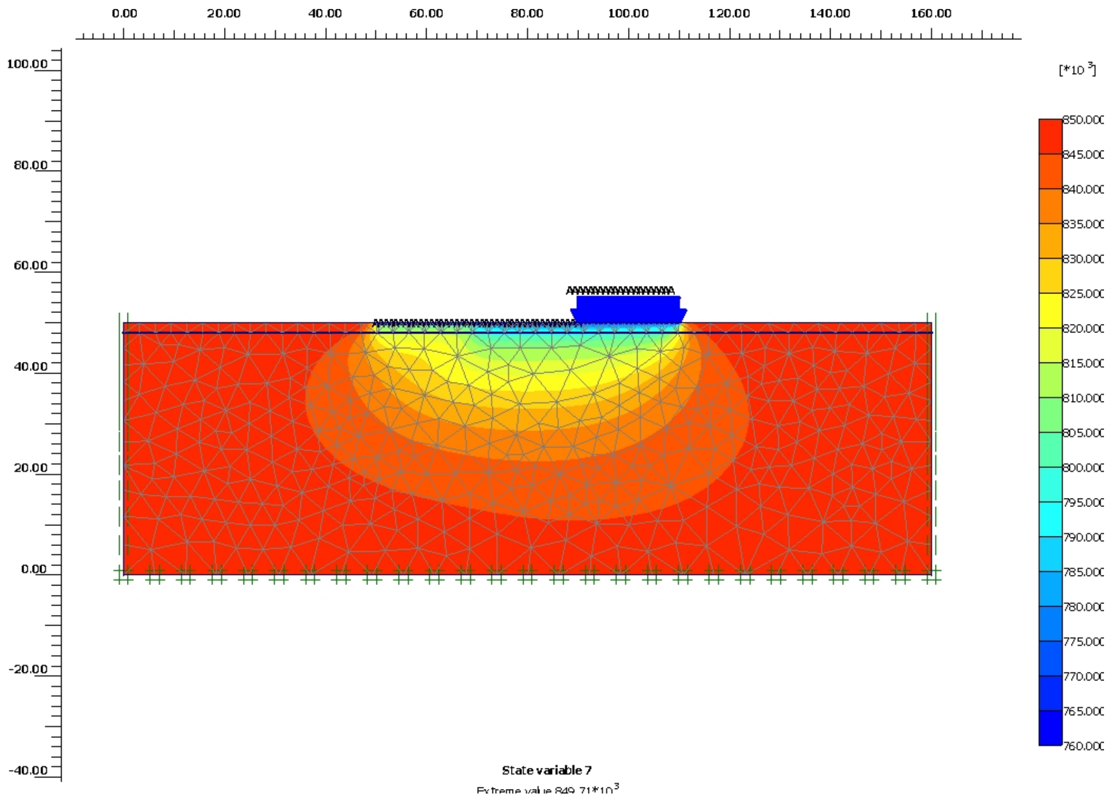

Fig. 4. StaPaC – Quantitative estimation of the compaction effect – Void ratio changes predicted with the hypoplastic constitutive equation of von Wolffersdorff

Table 1. *StaPaC – Quantitative estimation of the compaction effect – Soil mechanical material parameters for the hypoplastic constitutive equation of von Wolffersdorff*

Parameter:	Dimension:	OLD parameter set:	NEW parameter set:
γ_n	[kN/m³]	17,00	17,00
γ_r	[kN/m³]	20,00	20,00
B	[1]	0,99	0,99
k_x	[m/sec]	$5,00 * 10^{-5}$	$5,00 * 10^{-5}$
k_y	[m/sec]	$5,00 * 10^{-5}$	$5,00 * 10^{-5}$
ϕ_c	[°]	33,0	35,0
σ_t	[kN/m²]	5,0	5,0
h_s	[kN/m²]	1600,0	20,0
n	[1]	0,190	0,500
e_{d0}	[1]	0,440	0,470
e_{c0}	[1]	0,850	0,973
e_{i0}	[1]	1,000	1,12
α	[1]	0,250	0,10
β	[1]	1,000	3,00

Legende:

γ_n : Specific weight at partial saturation
γ_r : Specific weight at full water saturation
B : Skempton pore pressure factor for isotropic loading
k_x : Hydraulic permeability for flow in horzontal direction
k_y : Hydraulic permeability for flow in vertical direction
φ_c : Friction angle in residual state
σ_t : Tensile stress limit in the granular skeleton
h_s : Granular hardness
n : Compression exponent
e_{d0} : Void ratio at densest state in the granular skeleton at reference stress
e_{c0} : Void ratio at critical state in the granular skeleton at reference stress
e_{i0} : Void ratio at isotropic compression state in the granular skeleton at reference stress
α : Exponent describing the density influence on the shear strength and dilatancy
β : Exponent describing the density influence on the incremental stiffness

Quantitative estimation of the compaction effect with the static partial compaction (StaPaC)

Based on theoretical modelling, quantitative densification effects from static partial compaction (StaPaC) of liquefaction susceptible sands in dumps of former lignite opencast mines have been studied. In two dimensional plane strain calculations with the finite element method implemented in the programme system PLAXIS-2D, the hypoplastic constitutive equation for sands in the form proposed by von Wolffersdorff has been utilized, allowing for the modelling of deformation processes in soils depending on the prevailing effective stress state and density [von Wolffersdorff, 1996]. The hypoplastic material parameters of typical liquefaction susceptible sandy dump soils from former lignite opencast mines are presented in the table 1, derived from older and newer experimental studies.

In the theoretical model, a static load with a normal stress of σ=75[kN/m²] has been assumed under a surface load with a width of 20m. During the movement of the surface load, a continuous spatial consolidation process takes place and the excess pore pressures dissipate depending on the hydraulic permeability properties of the liquefaction susceptible dump soil.

Figure 2 shows the change in the void ratio due to the ground improvement effect with the static partial compaction (StaPaC) depending on the initial void ratio in the ground in a depth of 10m. Above this depth, a significantly higher densification effect can be expected, leading to an effective stabilization in the depth range, where low effective stresses and high water saturation ratio lead to a high liquefaction susceptibility of the soil. Additionally, high density changes will occur in the naturally saturated soil layer directly beneath the surface load, reducing latent residual liquefaction risks from later changes in the water table level.

Figure 3 shows the displacement field and figure 4 the void ratio change due to the densification effect of a marching static load on the surface with a dimension of 20m width. It is obvious, that the mechanical depth influence reaches approximately the geometric size of the surface load. The densification effects are the strongest below the ground surface and decrease slightly with increasing depth. The resulting density field is homogeneous and all soil particles have been definitely reached by the ground improvement effect.

Alternative stabilization methods

The position of the ground water table level is a crucial decisive factor in the selection of potential stabilization methods. The soil stabilization with compaction is strongly connected with settlements of the ground surface. If the ground water table takes a very high level, the ground surface can come very near of drop below the water table, dominantly changing the geotechnical characteristics of the site.

The current position of the water table level may also force an undesired change in the way of the site utilization strategy, such as agricultural or forest economic use. With soil compaction, also additional undesired water surfaces such as locally wet regions can emerge.

Especially in the case, when buildings or infrastructural facilities have previously been erected on liquefaction susceptible sites, the application of compaction and induced settlements would lead to a mostly prohibitive deformation in the building structure. In combination with a high water table level, the serviceability of the building could be endangered in connection with the soil stabilization measures.

If the option of soil compaction must be dropped among the geotechnical stabilization methods on a given site, the soil grouting in the liquefaction susceptible ground remains the final and unique ground improvement alternative. The grout material can fill up the void space in the soil and reduce the water saturation ratio. The grout material can also lead to a cementation of the granular skeleton building up a cohesive strength component additionally restraining the liquefaction failure mechanism. Due to a change in the void space filling, grouting can be expected to lower the hydraulic permeability characteristics of the treated ground.

The economic efficiency of the grouting stabilization of liquefaction susceptible sites depends on the effort in order to install the grouting tube equipment. Due to the usually very low cone penetration resistances in liquefaction susceptible soils, the installation of the soil grouting tube equipment can be mainly carried out with low effort, leading to an economic ground stabilization method. Below the water table level, the grouting tube can even fall without any resistance into the loose water saturated granular soil under fast undrained loading.

The grouting pressure is a very important stability question and design parameter of a ground grouting operation. High grouting pressures can lead to locally very high and dangerous excess pore pressures and trigger a liquefaction failure. In a ground grouting operation for the stabilization of liquefaction susceptible soils, basically two strategies can be followed. On the first hand, grouting can be applied with a high distance of the grouting points to each other. With high grouting pressure, cracks can be introduced into the liquefaction susceptible soil and filled up with the stabilizing material, leading to a rib skeleton structure with high shear strength. With this method, grouting can be applied for the stabilization of liquefaction susceptible soils over large surface areas with a moderate increase of the shear strength. On the second hand, grouting can be applied with a low to very low distance of the grouting points to each other. With a low grouting pressure, the voids in the liquefaction susceptible soil can be filled up with the stabilizing material, leading to a column structure with high shear strength. With this method, a preferably local stabilization under foundations of already existing buildings can be carried out leading to a strong local increase of the shear strength.

In the grouting stabilization of liquefaction susceptible soils, the selection of the grouting material is also a very important question. The grouting material must be environmentally compatible, must exhibit a strong stability against leaching out in the ground water and must be economically advantageous at the same time. The optimum solution would be the utilization of a harmless industrial residual material that would reach substantial shear strength and would have a long term leach out stability in ground water at the same time. Lignite ashes as residuals from coal energy production have been successfully tested but their environmental compatibility is still questioned.

Summary and conclusions

The spontaneous liquefaction of soils belongs to the most dangerous types of failure in geotechnics. A local liquefaction failure can occur without any previous signs and trigger a harmful mass movement extending to large areas.

Neither liquefaction susceptibility nor the danger of a spontaneous liquefaction failure will be reduced over time, as it is the case in other geotechnical applications, where a certain “natural attenuation” leads to slightly increasing safety factors with soil age. The danger for a spontaneous liquefaction failure can prevail over long time periods in a soil body and it can be triggered, when suddenly all geotechnical prerequisites are fulfilled at the same time.

For the stabilization of liquefaction susceptible dumps of former opencast lignite mines, the optimum solution is a compaction of the soil skeleton. Prescribing the critical density, the pressure dependent density limit, where dilatancy sets in at shear loading, as the compaction goal level, is economically not feasible and would lead to undesired large deformations in the subsoil. The significant reduction of liquefaction susceptibility in the dump material can be reached with a slight, uniform and sufficient density increase over large areas, leading to a sufficient reduction in volume changes at subsequent shear loading and avoiding a spontaneous liquefaction failure.

The selection of an appropriate ground improvement method is difficult, as the geotechnical information level on the dumps of former lignite opencast mines is usually quite low. Those ground improvement methods are clearly in advantage, where the compaction effect can be estimated beforehand and from the observed ground improvement results, the efficiency of the resulting ground compaction and the increased stability of the treated ground can be determined.

For the stabilization of liquefaction susceptible soils with high groundwater table levels, dynamic ground improvement methods show application limitations and their use can lead to undesired displacements of the ground surface or even to liquefaction failures due to the spreading of the induced wave field.

The recommended ground improvement technique for the stabilization of liquefaction susceptible dumps of former lignite opencast mines with compaction, the static partial compaction method (StaPaC) introduces a slight density change into the soil skeleton with a moving load on the ground surface and a connected spatial consolidation process.

The static partial compaction (StaPaC) method unifies ground exploration, densification and quality control in one single process and is economically feasible to induce the necessary and sufficient density change level into liquefaction susceptible dump soils of former opencast lignite mines that their economic reuse can be guaranteed on a very low latent residual risk level.

If the option of soil compaction must be dropped among the geotechnical stabilization methods on a given site, the soil grouting in the liquefaction susceptible ground remains the final and unique ground improvement alternative. The grout material can fill up the void space in the soil and reduce the water saturation ratio. The grout material can also lead to a cementation of the granular skeleton building up a cohesive strength component additionally restraining the liquefaction failure mechanism. Due to a change in the void space filling, grouting can be expected to lower the hydraulic permeability characteristics of the treated ground.

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Recommended for publication by Editorial board.