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Stabilization of Landslides Sliding Layer Using Electrokinetic Phenomena and Vacuum Treatment

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Abstract: The article presents the efficiency of application of cohesive soil dewatering for increasing its resistance to shearing, which influences the mass stability of flysch rock. Studies of the typical soil constituting the contact layer initiating the sliding of existing Carpathian flysch landslides were conducted. This aspect was examined because the water content of this soil decides its ability to form a sliding surface of the landslide block soil. The soil was subjected to changes in water content by dewatering with different methods. The influence of dewatering by self-acting gravitational outflow was examined and was additionally aided by two selected methods: electrokinetic phenomena and vacuum treatment. The model study conducted demonstrates the influence of the abovementioned dewatering methods on increasing the strength parameter of the soil at the contact layer in which sliding surfaces can be created. The paper also demonstrates the degree to which the application of the vacuum and electrokinetic treatment caused by DC current voltage influences the draining, decrease of plasticity, and increase of soil shear stress resistance. The application conditions and increase in effectiveness due to the application of the studied methods were determined. The proposed methods allowed for the strengthening of slopes for two exemplary landslides which formed in the area of occurrence of the Carpathian flysch.

Keywords: slope; stability; electrokinetic; vacuum; soil model tests; soil dewatering

1. Introduction

Studies of issues related to the influence of electrokinetic phenomena have been carried out for the past century Horvitz 1939 [1]. Also, in 1949 [2] and 1961 [3], Casagrande described the practical application of the electrokinetic processes for clay soil. Studies conducted by Ukleja 1972 [4] and others show that this method is very effective for these kinds of soils. The idea of the electrokinetic treatment (ET) process (in relation to geotechnical issues) basically covers the following three phenomena:

- **Electroosmosis** is based on the flow of ground water ions (diffusive and free) as a result of an electric field rising, caused by DC, in the direction from the anode to the cathode. Electroosmosis is the most important process for the successful dewatering of sediments.
- **Electrophoresis** depends on the displacement of negatively charged colloidal size particles of the soil environment from cathode to anode (anaphoresis) or of positively charged ones from anode to cathode (cataphoresis).
- **Electromigration** is the transport of ionic species in the pore fluid and is the main mechanism by which an electrical current flows through sediment. Electromigration also includes the movement of ions produced by electrolysis toward the oppositely charged electrode.

All these processes occur simultaneously in soil and are caused by direct current flow with small amperage and low voltage.

This paper presents an original approach to analyze the critical part of a landslide, that is, the contact between two soil layers: (i) the static consolidated layer; (ii) the unconsolidated, wet, unstable layer. To analyze this special kind of soil and the impact of dewatering using electrokinetic treatment (ET) and vacuum, it was necessary to build a special stand. This laboratory stand had to be part of the natural contact layer with all the conditions that exist in nature. So it had to be a 1:1 scale laboratory stand containing the critical part of a landslide. The studies described in the paper were based on this assumption, the author's previous experience, and experiences described in the literature concerning the following groups of issues.

1.1. Applying Electrokinetic Phenomena to Soil Consolidation

The mechanism of action of electrokinetic phenomena is well studied. However, EC application methods and the variety of baseline conditions have prompted scientists to conduct many new studies, especially since most of the experiments already carried out have given very promising results.

1.1.1. Some of the Experiments Studied ET at Bench-Scale

Many studies of ET in soil dewatering have been carried out during recent years. Some interesting examples that are connected with the issues presented in the paper are shown below.

Lo et al. 1991 in [5,6] conducted complex experimental studies on osmotic strengthening of soft plastic clay. The efficiency of these treatments and the process mechanism were determined. The results of this study demonstrated that the distribution of induced voltage and vacuum of the pores along the sample are constant at continuous current flow in the whole sample. This demonstrates that the construction of an electrode in the tool applied during the study was efficient. The electroosmotic consolidation curve resembles the conventional consolidation curve, and the preconsolidation pressure was increased by 51–88%. The shear strength increased in the range of 50–172% and the water content diminished by 30%. Also, the technique of turning the electrodes was applied here, and a relatively uniform increase of the electroosmotic actions between the electrodes was observed. It was established that the studied process may have wider application, but requires technological improvements.

One of the anticipated effects of the application of ET is strengthening the consolidation of cohesive soils. The consolidation processes studied by Hong and Shang 1998 [7] demonstrated that horizontal drains are frequently used in soft clayish soils to accelerate the consolidation. However, they produce a differential effect which depends on a few variable parameters, that is, consolidation factors and the horizontal and vertical permeability to water. Meanwhile, the water permeability of soil is a parameter that we can increase by using ET.

Many studies have been conducted to increase the efficiency of the electrokinetic processes influencing the rising of the physical parameters of cohesive soils. Chen and Murdoch 1999 [8] carried out field studies of the operation of horizontal electrodes applied with respect to post-glacial clay. An electroosmotic flow was applied and its influence on the soil properties was characterized (e.g., electric conductivity and pH). The obtained results confirm the effectiveness of the utilization of horizontal electrodes at small depths.

Testing the electric flow efficiency during electroosmosis was also the subject of interest of Mohamedelhassan and Shang 2001 [9]. A number of electrode materials were tested under various power supply conditions. The electroosmotic test was designed and executed in such a way as to measure the electroosmotic flow triggered under known boundary conditions. Six different kinds of electrodes were tested. In the results, it was noted that voltage losses depend on the anode material and are smaller for metal anodes (steel or copper) than for carbon anodes. The electroosmotic water permeability coefficients are relatively independent from the electrode materials and can be controlled by adjustment of the electric field intensity in soil. It was demonstrated that the application of constant cycles of power supply generates higher electroosmotic flow than the same continuous voltage applied once. The electroosmotic water permeability coefficient is maximal when using the 2-min cycle power on/1 min off.

Moreover, Glendinning et al. 2005 [10] described the possibility of using the electroosmosis phenomena in connection with geosynthetics to raise the soil parameters at the stage of designing reinforced embankments or dumps.

Reddy et al. 2006 [11] described laboratory research on highly contaminated sediment which had accumulated in Indiana Harbor USA. The tested sediment possessed very high moisture content and very low hydraulic conductivity, which caused consolidation to occur slowly. The feasibility of using an electroosmotic dewatering technology to accelerate dewatering and consolidation of sediment was investigated. A series of bench-scale electrokinetic experiments were conducted on actual dredged sediment samples using gravity and electric potential, and the effects of the addition of polymer flocculants on dewatering of the sediments were examined. The results showed that electroosmotic dewatering under an applied electric potential of 1.0 VDC/cm could increase the rate of dewatering and consolidation by an order of magnitude as compared to gravity drainage alone. Amending the sediment with polymers enhanced this dewatering process.

1.1.2. Some Experiments Studied Effects of ET on the Theoretical and Numerical Models of the Soil

Recently, instead of conducting laboratory tests, some researchers have started to work on numerical models. Their results are compared with theoretical and laboratory tests. Some of them provide interesting conclusions, which are presented below.

A two-dimensional consolidation model was described by Su and Wang 2003 [12]. Gabrieli and Alshawabkeh 2008 [13] demonstrated the influence of the boundary conditions on neutralization of over-pressure in pores during application of the ET process in soil. Deng and Zhou 2012 [14] presented a section-linear model based on the finite differences method of single-dimensional electroosmotic consolidation, called ECS1, based on Euler's constant of the coordinate system. The model is able to describe nonlinear physical soil changes and mechanical and electrical properties and to estimate the trends of electric potential, resistance, pore water pressure excess, and the level of consolidation. Zhou et al. 2013 [15] created a single-dimensional numerical model describing consolidation, which was verified experimentally. A large influence of ET on pore water pressure and acceleration of the consolidation process was demonstrated.

The consolidation of soil is not the only effect of ET. For example, Al-Hamdan and Reddy 2008 [16] described an additional effect obtained with the use of ET in soil. Subjecting soil to this process is one of the developing technologies that offers the possibility of cleaning soil contaminated with heavy metals such as chromium, nickel, and cadmium. It is a kind of electrokinetic reclamation of both cohesive and loose soils.

The effectiveness of electrokinetic treatment depends on the complex physical–chemical interaction between soil particles, interstitial fluid, and pollutants. Gargano et al. 2018 [17] presented experimental laboratory results obtained by inducing consolidation in a fine-grained dredged material by mechanical and electrokinetic treatment. The experimental results were numerically simulated, showing the ability of Lassec1 to reproduce the coupled mechanical and electrical consolidation. In other research, Gargano et al. 2020 [18] performed electroosmotic tests in oedometer conditions on a clayey soil in a special oedometer, adopting a pore fluid with different salt concentrations. The results show that the addition of soluble salts in small quantities (up to 8 g/L) can improve the electroosmotic consolidation of soft clay. On the contrary, excessive salinity reduces the efficiency of electroosmotic dewatering. The optimal salinity content was then determined.

1.2. Vacuum Application for Soil Strengthening

Vacuum treatment is the next way to raise the soil strength characteristics. For instance, Shang et al. 1998 [19] presented the construction, operation, and results of a project of soil reinforcement using the vacuum method. The reinforcement was realized with a vacuum on areas with surfaces ranging from 5.000 to 30.000 m^2. The effects on raising the soil parameter were demonstrated for the average consolidation layer thickness of 2.0 m. A two- to fourfold increase in the shear force was achieved in relation to soils not subject to dewatering. The study shows that the vacuum method is an efficient tool for consolidation of plastic clayish soils over a large area. Similarly, in their studies, Deng and Xu 2010 [20] attempted to determine the influence of vacuum treatment on cohesive soil consolidation, connecting the vacuum method with dynamic compressing. As soil compression requires high consumption of time and labor, this method was applied in order to accelerate the consolidation process.

A slightly different solution was applied by Li et al. 2001 [21] and 2009 [22]. They described tests on the application of vacuum for consolidation and dewatering of cohesive soil pores using geosynthetics. The method proved to be very efficient, which was confirmed by tests executed on geosynthetic nets in a horizontal layout.

Some researchers, considering the effectiveness of both ET and the vacuum method, have tried to use the two together. Thus, Wu and Hu 2011 [23] developed two analytical (one-dimensional) models, the first a model of vacuum preloading binding with electroosmosis and the second an axisymmetric model of vacuum preloading binding with electroosmosis. The theoretical solutions of the two models were derived, and numerical FEM models were developed. Comparison of the results showed that the theoretical solution was highly compatible with the numerical simulation. It was noted that in the process of vacuum preloading in combination with electroosmosis, a negative pore pressure is generated in the model. The pore pressure of different points in the model is different and the pore pressure of points far from the vacuum boundary and the cathode shows a faster rate of change than other points.

Both pore pressure and displacement of points in the model change very fast at the beginning, but over the course of time, the rate decreases and the displacement gradually becomes stable. As water comes out of the model, the soil skeleton is compressed and the hydraulic conductivity will decrease simultaneously, causing a decrease of the drainage rate. These conclusions are similar to the observations from laboratory tests presented in this paper.

1.3. Issues Related to the Control of Structural Landslides with a Determinate Slip Contact Layer

Stability issues of slopes and dams with regard to variability of their soil layer parameters, which depend on the content and flow of water, were studied by Lian-Heng et al. 2015 [24], Jian and Hong-Jian 2014 [25], Kuangmin and Sheng 2015 [26], and Jiuping and Cuiying 2015 [27], among others. A substantial issue allowing for proper selection of a method and analysis of the particular landslide is knowledge of the geological structure of the rock mass subject to landslide. This was shown by, for example, Poisel et al. 2009 [28], who conducted an analysis of the structure and mechanism of formation of a mountain landslide on the basis of geological structure. In another example, Al-Homoud et al. 1997 [29] described the stabilization of a high building. Salcedo 2009 [30] described a road bridge catastrophe caused by a large landslide crossing a road section. In both examples, the slope was located on a determinate slide layer. The most complex problem concerns landslides of the structural type (landslides with a determined slide surface due to the specific combination of soil layers).

This movement occurs on the sliding surface, which is usually constituted by a plastic ceiling of silt or clay layer. Such landslides are usually activated after heavy rainfall supplying water to the contact layer, creating sliding surfaces in its floor. This kind of contact layer of soil was researched in the laboratory tests presented below.

The study results presented above are proof of the complexity of the issues connected with the stability of a scarp in cohesive soils. The applied methods of raising the strength parameters of these soils are effective in a way, but all have their limitations. Their efficiency is sometimes only limited in survey, due to the large number of external factors that influence the results of such studies. Thus, sometimes the solutions are frequently not used because the efficiency (which should be intuitively correct) is difficult to verify at their application for improvement of scarp stability. One of these methods is the electrokinetic method of soil dewatering and the second is the vacuum method. These methods are rarely used due to difficulty in assessing their efficiency, especially when some other means of preventing landslides are simultaneously applied (gravitational dewatering, anchoring, buttresses, etc.). An attempt to study this problem with respect to Carpathian flysch soils was undertaken by the author by conducting a number of studies and observations of landslides in the field and under laboratory conditions (at model scale).

This article presents the issues concerning the application of electrokinetic and vacuum treatment to strengthen the soil constituting one of the flysch layers. On the basis of the results included in the publications up to now, an attempt was made to use both ET and the vacuum method to increase the shear strength of these cohesive soils, which constitute the weakest link of the multilayer flysch. As the soil strength depends on its state and water content, the key problem was dewatering of this soil. Thus, the principal objective was experimental verification of the application of both methods for dewatering soft plastic and plastic cohesive soils.

This laboratory stand needed to be part of the natural contact layer with all conditions that exist in nature. So it had to be a 1:1 scale laboratory stand containing the critical part of the landslide. This tested part is a special kind of soil because it decides the stability of whole landslide body independent of its upper layering. Therefore, this thin layer of soil is sometimes the most important for the whole mass of the slope because the condition of this layer decides it stability. However, the strength of this layer is mainly influenced by its water content. So dewatering by using ET and the vacuum method could be a good solution to stabilize the landslide body. Because the flysch is the type of soil where many potential contact layers exist, this kind of soil was taken into account in the model tests.

The presented kinds of soils were formed as a result of geological deformation and erosion of the primarily formed flysch structures and defined as the primary soil (PS) (Figure 1, item 6). They constitute surface layers of large areas of the foothill areas. They are characterized by variable strength features resulting from their internal structure and sensitivity to changes of the ground water table related to periodical rain and drying of the soil. In particular, the soils formed as the product of secondary sedimentation of the flysch layers in alluvium and breccia on slopes and in foothill area terraces are unsuitable for preserving stable conditions. These soils formed after erosion of the flysch can be named transformed soil (TS) (Figure 1, item 1).

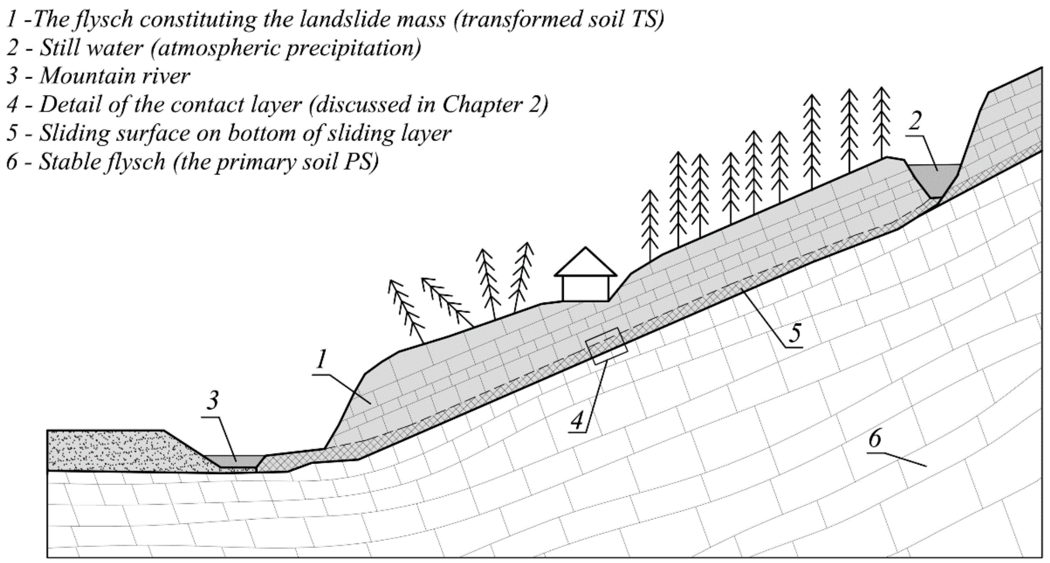


Figure 1. Typical cross-section of a landslide in a flysch structure.

The main task in the stability analysis of the areas of flysch occurrence is to determine the parameters of the TS strength formed in the breccia of the PS primary flysch, converted during the secondary sedimentation, or due to the effect of movement of an active landslide. Landslides and flows of these formations constitute the main hazard for the stability of objects of economic infrastructure and commercial areas. Studies lasting a few years in this respect by the author (Ukleja 2006) demonstrated that obtaining reliable strength parameters with the traditional laboratory study methods applied in geotechnics (routinely executed as for uniform soils) frequently leads to unsatisfactory and usually inadequate results. For this reason, the author decided to conduct model tests. In these tests, an attempt was made to copy the processes observed in natural landslides and to compare their adequacy with model conditions. The tests were carried out under the same conditions as in nature at the same scale so that the research and all the tested methods would be comparable.

2. Description of the Processes Changing the Strength Parameters in the Soil Constituting the Flysch

The key issue for selecting a correct method of stopping a landslide and its stabilization is the possibility of determining the parameter changes of the TS strength, which is subject to the strengthening process. In the case of these soils, a decisive factor is water content, which we can influence. It was necessary to elaborate a special methodology enabling modeling of the phenomena occurring in the crucial areas of the rock mass, which constitute the so-called "weak link" in the process of self-stabilization of a slope. Such areas are the sliding surfaces of some flysch layers, on which sliding of the neighboring layers may occur (Figure 2, item 1).

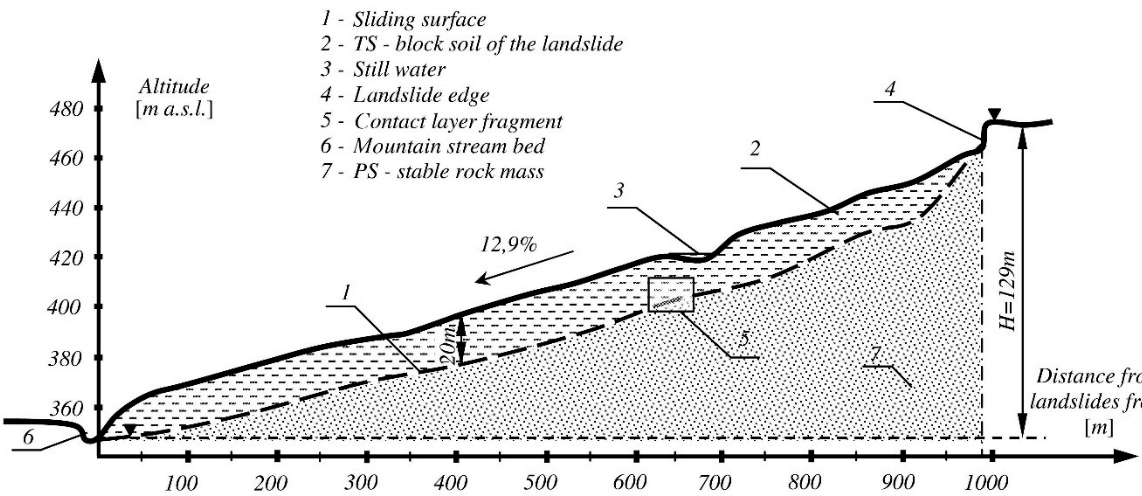


Figure 2. Cross-section of the landslide (Zapadle, Poland).

Therefore, a special apparatus was constructed to allow modeling of the TS structure, with the possibility of changing the water content in the soil and the ground water table level. It was advisable to study the soil strength parameters in relation to variable water content in the soil, depending on the atmospheric conditions.

On the basis of field studies lasting a few years, field studies on active landslides formed in the flysch, in the area of the Low Beskids in the Carpathians (Stryszawa—Figure 1; Zapadle—Figure 2), it was noticed that the landslide mass was constituted of flysch consisting of lump conglomerates and cohesive billets mixed with rocky soils. These soils feature a variable structure over time and variable strength parameters, depending on atmospheric conditions (Figure 3).

The soil of the landslide mass is usually a mixture of silts including intrusions of weathered soft rocks. These soils demonstrate a lump-billet structure, which consolidate in the soil, even after "passing" the plastic state (fluency state) caused by hydration of the rock mass. It occurs between the long-lasting rainy and dry periods. The consolidated lump-billet structure of mixed flysch TSs causes strengthening and acceleration of their hydration processes during rainfall. This is related to self-sealing of the soil for water flow with simultaneous deterioration of the strength features. The rainless period causes recurrent soil drying and formation of fissures between the lumps (soil billets) and their clearance. This strengthens the soil and enables deep infiltration of water during the following rain period. Knowledge of these processes may be used in the case of application of rock mass dewatering by electrokinetic or vacuum treatment, as these treatments create the conditions for intensifying the dewatering process of these kinds of soils.

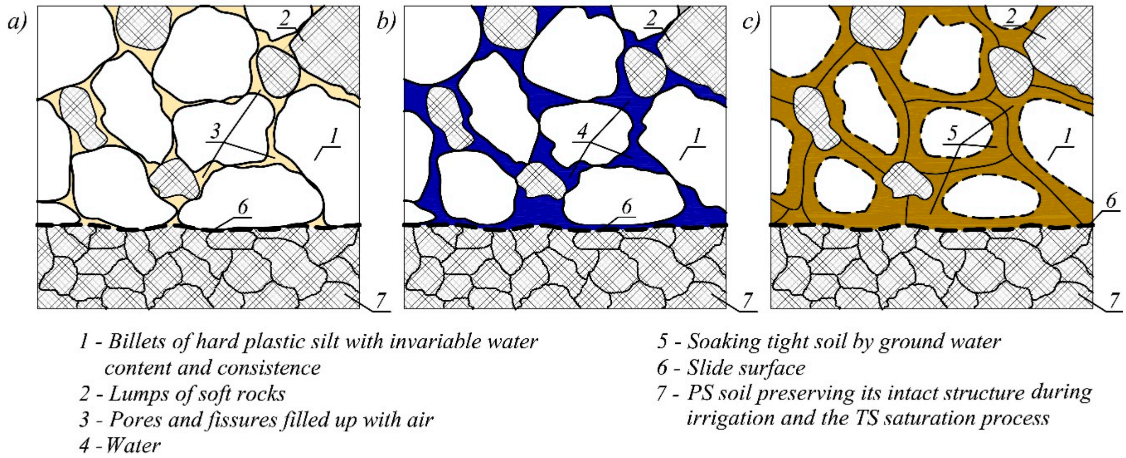


Figure 3. The process of flysch transformation before and after the loss of slope stability in the transformed soil (TS) structure of the contact layer: (**a**) TS in the dry period, (**b**) TS after irrigation, (**c**) TS after soaking (at the time of slide occurrence).

In the soils of the contact layer, under which the landslide sliding surface is formed, three principal TS structure phases can be differentiated depending on their water content:

- Phase I, occurring in a long-lasting dry period or during light precipitation (Figure 3a). In this phase, the breccia and silt lumps conglomerated earlier and formed during erosion of the primary flysch layers lose a large amount of water content (moisture) and finally crack. As a result of drying, the strength parameters increase in the TS, causing its periodic stabilization.
- Phase II, occurring after long-lasting rainfall (Figure 3b). Precipitation water in this period penetrates the cracks that formed earlier. Ponds and sloughs form in terrain depressions (water hollows) supplying ground waters under pressure. This process causes the plastic state of silt soils to be bonding "not crumbled" TS lumps.
- Phase III, occurring after a long period of rainfall (Figure 3c). In this phase, bonding and silt lumps forming the landslide layer on their external layers undergo fluency. This causes the landslide section to behave as soft plastic soil in its entire thickness. This allows hard lumps in the plastic landslide mass to move and turn in spite of themselves.

A slide plane may be formed at the consequent positioning of the layers of the PS flysch with respect to slope inclination (Figures 1 and 4) on the contact layer floor. Their strength parameters may be more adverse than those of the soil in the sliding mass of the landslide.

The above discussed instances of occurrence of the flysch structure point to the need to consider these phenomena. Attention must be paid to the following aspects in the studies determining the soil parameters to be used in stability calculations:

- the real structure of the flysch formations in the existing landslide section,
- determination of the physical and mechanical parameters of the PS flysch forming the material of the TSs and in the contact layer near the slide plane,
- the geological structure of the intact rock base (the range of change of the hydrogeological and hydro technical conditions).

(a)

(b)

Figure 4. Example of the structure of a typical Carpathian flysch landslide (Stryszawa, Poland). (**a**) Rhythmical variables of flysch layers; (**b**) Opened sliding surface under the contact layer.

3. Study Methodology for Determining the Credible Physical and Mechanical Parameters

3.1. Initial Assumptions for the Studies

Examining the physical and mechanical parameters of the cohesive soils and especially the TS flysch is a very complex issue. In such cases, we are dealing with a mixture of soils with different structures. The soils that occur here are from substantially cracked and weathered sedimentary rocks (silt shale, marl, sandstone, conglomerate, mudstone, etc.). They are also formed by silts including soft rock bits transformed as a result of the geological processes.

In the accepted methodology of determining the credible parameters of the tested flysch soils, it was attempted to take into consideration the specific structure and texture and adverse action of pressing fissure water. Observations of some landslides occurring in the Carpathians led to the conclusion that the factors causing their formation in the areas of occurrence of the flysch structures are chiefly:

- consistent with the slope inclination of the stable base, on which a thick layer of weathered soft rock (to depth of 20 m) lies. The layer forming the landslide mass is usually composed of silts or dust clays including breccia and fragments of weathered soft rocks. Weak contact layers are formed from them, creating sliding surfaces that initiate landslides;
- the alternating level of the ground water table occurring in rock fissures of the cracked base. This water acts on the weathered soils with supplanting, filtration pressure, and hydrostatic pressure. It occurs in periods of long-lasting rain and snow melt, initiating the plastic state of the soil layers with a disturbed structure;
- static loads, such as the weight of municipal, engineering, hydrotechnical, and industrial structures, power objects, and woods. These objects ballast the wedge of a block soil in case of occurrence of such factors;
- deterministic and nondeterministic dynamic loads. They are caused by loads of roads and railways, heavy industrial and construction objects (pile drivers, hammers, turbines), seismic tremors, and even lightning tremors. They may constitute an impulse to start a landslide in the case of simultaneous hydration of the rock mass.

A considerable part of the listed factors exerts an influence by destabilizing landslide processes. Therefore, it was necessary to model an appropriately constructed test stand. It was filled with real soils occurring in the landslide. It allowed the particular phenomena to be operated in a controlled way and especially allowed for modeling:

i. the shaping of various forms of secondarily structured flysch soils;
ii. the action of the electrostatic field created by DC current flow causing soil stabilization. Interferences from the surrounding rock mass were eliminated. These interferences may cause uncontrolled current flow, which would exert a negative effect on the results of the studies;
iii. the vacuum dewatering of the rock mass with a known structure and the kind of the soil as well as the conditions of its hydration;
iv. the filtration conditions of the ground water in the flysch with a differential form of reconstructed structure;
v. values of the variable normal stresses occurring in the contact layers at different depths of deposition.

Taking into account the special character of the soils forming the flysch, some basic assumptions were accepted in the studies:

i. hydrated soils with a reconstructed structure demonstrate rheological features. They are characteristic for sticky materials demonstrating small values of internal friction ϕ and large values of the apparent cohesion variable c in time (the apparent cohesion occurring in large soil deformations under loads);
ii. exceeding the border value of static stresses causes the occurrence of displacements in the contact layer soils, which results from a lack of proper cohesion of this layer. Proper cohesion occurs only in soils that maintain a durable, stable structure under the influence of loads;
iii. due to a change in the water content and loosening of the solid phase, the studied soils may have a twofold form: regularly consolidated and over-consolidated soils. The regularly consolidated soils are those in which the cohesion was not able to take place after transformation as a result of water acting in the soaked soil (Figure 3, item 5). The over-consolidated soils are those that have effective cohesion after prior consolidation, which features lumps of the soil contact layer (Figure 3, item 1);
iv. the soils taking part in sliding processes, chiefly constituting the cover of the rock base, which were not subject to consolidation processes, are subject to the principles expressed by Bishop-Skempton and expressed by Wilun in 1982 [31] using the following formulas:

- for the consolidated regularly soils

$$\tau_f = \sigma' tg\phi', \tag{1}$$

- for the over-consolidated soils

$$\tau_f = \sigma' tg\phi' + c', \tag{2}$$

It was assumed that:

$$tg\Psi = \frac{\tau_f}{\sigma'}, \ \Psi = arctg\frac{\tau_f}{\sigma'}, \tag{3}$$

and therefore:

- for the consolidated regularly soils

$$\Psi = arctg\frac{\sigma' \cdot tg\phi'}{\sigma'} = \phi' \tag{4}$$

- for the over-consolidated soils

$$\Psi = arctg\frac{\sigma' \cdot tg\phi' + c'}{\sigma'} = arctg\left(tg\phi' + \frac{c'}{\sigma'}\right) \tag{5}$$

where: ϕ' = effective angle of internal friction, c' = effective cohesion, $\sigma' = \sigma - u$ = effective stresses in the solid phase at the moment of shearing, u = pore water pressure in a sample at the moment of shearing, Ψ = effective angle of internal friction corresponding to the maximal border inclination of the sliding surface. When the inclination of the landslide mass slide plane is larger than Ψ, it is assumed that shearing of this contact layer will occur, initiating sliding.

Thus, the above assumptions were accepted in the studies as well as the fact that the studied soils often have a reconstructed structure, variable water content, and weathered intrusions of the primary soft rocks. In relation to this, in the laboratory studies it was attempted to model the character of the determined stresses adequately for the actual conditions. In the conducted studies, a special meaning was given to the correct way of determining the basic parameters of the contact layer soil. This nonstandard approach was connected with the specificity of the TS subject to constant changes inside the landslide mass. They were conducted by two selected methods applied in studies with a box apparatus used for direct shearing:

(a) Borowicka 1961 [32],
(b) Kezdi 1962 [33].

The Borowicka method depends on shearing the same sample in a box apparatus several times, in the same plane, at different normal stresses σ_1. Meanwhile the box of the apparatus with a sample is moved back to the initial position after each shearing. This makes it possible to obtain the so-called "residual" values of τ_r, ϕ_r, and c_r appearing in the shearing planes in which the slide occurs. It is a good way of mapping the behavior of the mechanism of the sliding surface during landslide movement or restarting its activity. The author's observations demonstrated that the residual values of the parameters τ_r, ϕ_r, and c_r commonly occur in slow-motion landslides, activated periodically in the flysch.

Meanwhile, the Kezdi method allows for determination of the shearing stresses τ in solid phase as a function of normal stresses σ_n with consideration of displacement in respect of move themselves of the apparatus boxes s in time t. The studies depend on shearing of the soil samples according to the following procedure:

(a) the examined sample is submitted to consolidation at normal stress σ,
(b) next, the constant shearing tension τ is applied and the displacement s is determined until it disappears, measuring the increase of deformation η *s/t* (where s = displacement in time t and t = the time in which the displacement occurs s),
(c) when η reaches a value close to 0, the test is considered finished and the displacement s is the "way of mobilization" of the soil for shearing.

The test is repeated in cycles for a larger value of τ each time. The value of maximal shearing tension (corresponding to the shear strength) $\tau_{max} = \tau_f$ is achieved when the displacement s proceeds in a continuous way, that is, when the increases η do not approach "0" but reach a constant value. The value is called the maximal way of mobilization of soils for shearing, and after it is reached, the soil achieves the maximal shearing stresses τ_{max}. The cause of the reduction in displacements under the influence of the shearing force (especially in cohesive soils) is shearing, which arises at one point first or in a certain section and then expands along the whole sliding surface. Thus, the Kezdi method considers mobilization of the whole soil structure during its shearing.

3.2. Selection of the Method of Determining the Physical and Mechanical Parameters of the TS

The physical parameters, namely the water content, consistency border, bulk density of soil, and the kinds of studied soils, were determined in compliance with the requirements of obligatory standards in this respect for soils. To determine the mechanical features (strength), an individually selected method was applied according to the specificity of reconsolidated soils of the landslide mass.

This made it possible to obtain credible parameters that were as accurate as possible to modeling working of the studied soils in real conditions. The Borowicka method was applied to determine the shearing stresses in soil (which takes into account the residual cohesiveness) [32]. In this method, it is necessary to perform shearing using the direct shearing apparatus. The content of rock chips in tested samples and the need to minimize influencing the pore pressure in the stresses shearing zone led to the need to apply the maximal number of movable frames of the shearing zone (numbering 7 pieces). Their task was to diminish the influence of the resistance of rigid rock chips on the result of shearing. This made it possible to obtain shear strength results close to the effective values in the slide layer. Additionally, to verify the obtained results, part of the tests was repeated by the Kezdi method. Comparison of the tests conducted with both methods helped to determine the influence of the selected method on the obtained results. The tests were conducted on samples with intact structure taken from selected representative spots and depths within the whole testing chamber. Meanwhile the natural water content of the soil was preserved.

3.3. Description of the Test Model and Testing Process

The main object of interest was the landslide in Zapadle (Poland; Figure 2). Samples of soil were taken from this landslide from a location with an intact structure and water content in the soil from the contact layer and were subjected to detailed laboratory tests. The test stand was made from soils collected for model testing and for mapping the character and parameters of the contact layer (mapping its condition in the direct neighborhood of the sliding surface).

However, there was an attempt to verify some of the results on the basis of the soil samples taken from the Stryszawa landslide (Figures 1 and 4) which occurred in the years 1997–1998 after long-lasting rainfalls.

Due to the complexity of the processes occurring in active landslides and a large number of factors influencing the rock mass in natural conditions, it was decided to conduct testing at model scale. Only this method of testing could provide credible results. It made it possible to control the influence of the introduced stabilization factors on the soil parameters (from which the landslide was built). The focus was aimed at the part of the landslide block soil representing the contact layer (Figure 2, item 5). Prior to this, ground penetrating radar (GPR) and inclinometric measurements were conducted to ascertain the occurrence of the soil mass slide placed over the contact layer. The crucial element preceding the model tests was correct formation of the soil in the test chamber. The soil destined for testing was taken from the active landslide. The places from which samples were collected were carefully marked, while transport of the samples to the laboratory required special treatments for the soil samples with natural water contents. Obtained soil was supposed to map the parameters of the landslide contact layer in the conducted tests. Therefore, it was necessary to bring the supplied soil to the state corresponding to the parameters of the contact layer. This effect was accomplished thanks to relevant soil formation (described below) in the test chamber by compacting the particular layers. In this way, mapping of intact soil layers was obtained.

A diagram of the test soil described by Ukleja in 2006 [34], on which the tests were conducted when realizing the research project, is presented in Figure 5. Due to its character, this paper is limited to discussing the most important results of these studies.

To map the real conditions, a two-segment box was created in model tests, including the test soil with the same angle of inclination as the landslide slope. It was filled with soil representative of the contact layer of the landslide. This soil was taken from the selected fragment of the landslide compacted in such a way so as to correspond to the real conditions. The formation of the soil in chambers was executed layer by layer through kneading, preserving the structure and consolidation as well as reconsolidated soil porosity of the landslide mass and especially the contact layer. The formation of the test soil was executed from the soil samples with natural water content by performing:

(a) soil homogenization and removal of oversized particles,
(b) filling of the chamber spaces with the test soil in layers with thicknesses of approximately 10 cm,

(c) systematic compaction on the whole surface of each layer with a compactor (approximately 3.5 kg) falling from 20 cm height,
(d) protection of the stand against drying,
(e) verification of the soil parameters ϕ, c, and γ in the initial state of the tests with respect to the soil located in the deposit.

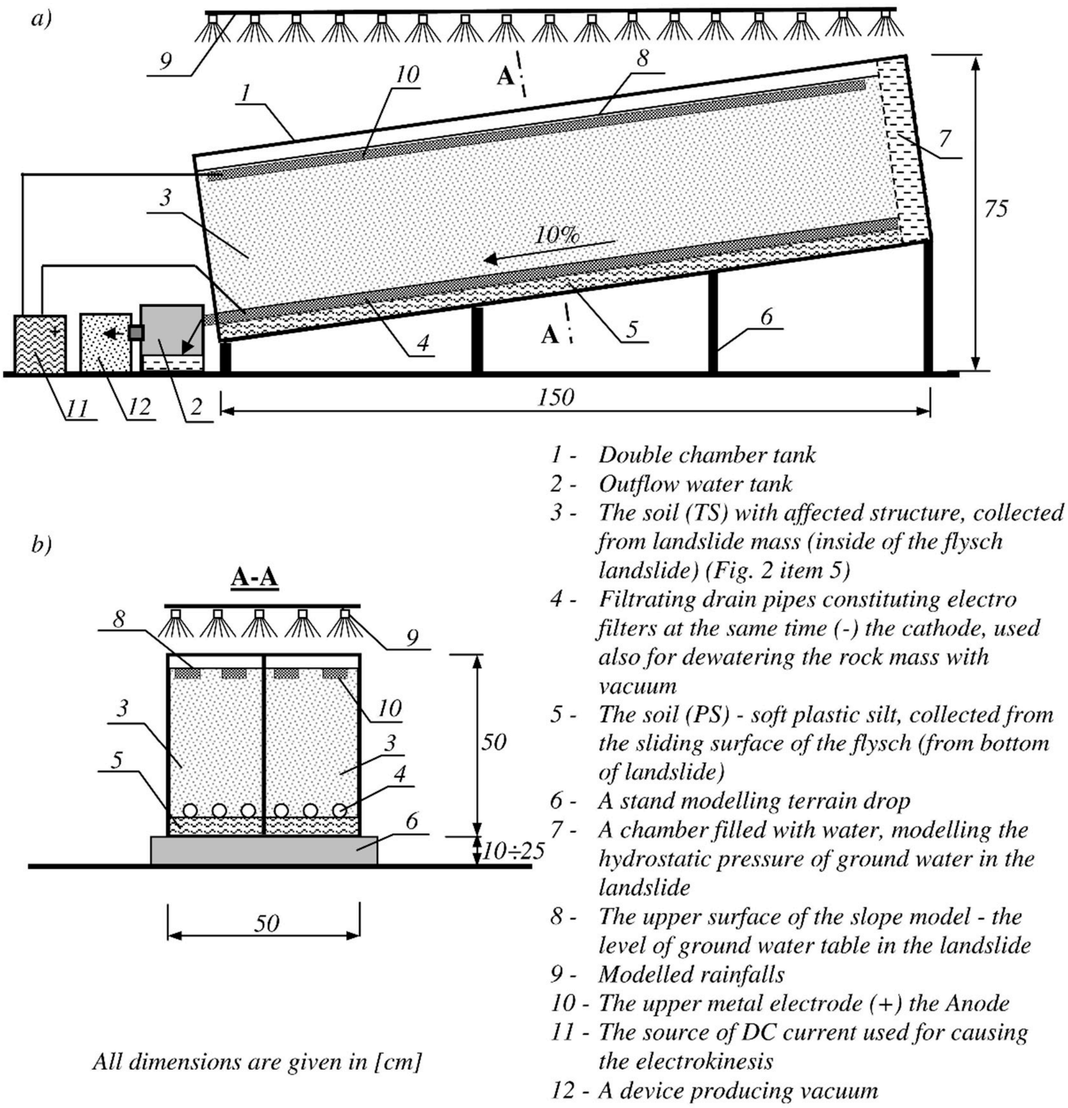


Figure 5. Diagram of the model test soil for testing the flysch landslide stabilization: (**a**) side view, (**b**) cross section A-A.

While performing the tests, the same irrigation, temperature, and water content conditions were provided in both chambers. One of these chambers was subject to checking tests and the second was the comparison background for it. This made it possible to conduct comparative tests between:

(a) gravitational dewatering and dewatering in which the ET process is also applied,
(b) gravitational dewatering and dewatering in which a vacuum is also applied,
(c) dewatering in which the ET process is applied and dewatering by application of a vacuum.

Of course, gravity acts all the time during all the tests. So, to separate it in the analysis of the influence of two methods of dewatering, it was necessary to perform two parallel tests in separate chambers using the ET method (chamber 1) and without it (chamber 2) or using vacuum (chamber 1) and without it (chamber 2). In this stage, the comparison was between the ET and the vacuum separately, and their dewatering ability was determined. In the second stage, both methods were directly tested together in the same conditions in two chambers at the same time. In this test, the differences in performance of the two methods were compared.

In all cases, dewatering was realized using steel drain pipes (perforated pipes covered with a fine filter with gravel cladding and steel net), modeling a Wellpoint Dewaterin System introduced into the soil by the jacking method along the slide layer. The application of geosynthetics, which may use ET and vacuum treatment, as presented by Gabrieli and Alshawabkeh [13] and Glendinning et al. [10]), was not taken into consideration as the dewatering method because of technical reasons (lack of the possibility of executing trenches and placing them in the contact layer). Dewatering drains (Figure 5 item 4 and Figure 6b) fulfilled the triple role of:

- gravitational drainage,
- electrodes in the ET process (cathode (–)),
- ducts for the generation of a vacuum in the soil (suctioning both water and air from the soil pores).

Figure 6. The test stand for conducting model tests: (**a**) two-chamber tank, (**b**) upper electrodes A(+) and lower electrodes K(−), (**c**) soil in the chamber after compaction, (**d**) the effect of ET application visible in the left chamber.

Electrodes in the form of flat steel bars (Figure 6b) placed on the surface of soil constituted the anode (+) in the ET process. The simulation of irrigation of the surfaces of the examined soil by atmospheric precipitation was realized by systematic showering from above. The hydrostatic pressure of ground water was modeled by the water pressure from the chamber filled up with this water (Figure 5a item 7), which passed through a perforated wall to the main chamber.

During the test, a DC current was used to generate the ET with a voltage of U = 24.0 V and current of up to I = 3.0 A. The vacuum values applied in the test were within the range of 0–0.05 MPa.

In the initial period of tests, a continuous vacuum was applied. However, it soon turned out that much better results were obtained by alternating a vacuum during intensive leaking and then short breaks of vacuum after leaking disappearance. These actions were then repeated until the leaks completely disappeared.

During the whole series of different test sets, cycles lasting two weeks each were used. During each cycle, samples of the soil were taken from different depths of the tested layer and subjected to standard tests of water content and soil strength standards in the Direct Shear Test Apparatus and Triaxial Shear Test Apparatus. Testing in the direct shearing apparatus was conducted by the Borowicka [32] and Kezdi [33] methods.

During these tests, shearing of samples with a natural structure was conducted for the stresses occurring in the shearing zone (slide) with the values:

- σ_1 = 100 mm,
- σ_2 = 200 mm,
- σ_3 = 300 mm,
- σ_4 = 400 mm.

Stresses σ_H coming from the hydrostatic pressure caused by water pressure in fissures in the rock base transferred to the mass wedge (causing its displacement) were assumed to be in the range of 0–150 kPa with intervals of 50 kPa. The parameters of the soil slide layer were determined at the same time with respect to the depth of its deposition 5, 10, 15, and 20 m below the surface terrain.

The basic soil parameters obtained, namely the effective cohesion c', effective internal friction angle ϕ', and water content w, taking into consideration the consolidation and hydrostatic pressure, made it possible to determine the values of Ψ (effective internal friction angle corresponding to the maximum border inclination of sliding surfaces) for each tested soil sample using Equation (5).

4. Analysis and Discussion of Test Results

At the outset, before starting the tests, pilot tests were carried out to select the optimal apparatus and equipment to reach the maximum effect of soil drainage. This involved, for example, the selection of the right current and the preparation of electrostatic precipitators and surface electrodes, as well as planning their distribution during the induction of the ET process to increase its efficiency. In the vacuum method, it was important to answer the question of what values of suction pressure can be achieved practically in the soil to achieve the maximum effect. It turns out that the efficiency of ET decreases gradually over a long period of time (approximately 14 days), and that the effect of vacuum expires in a short time, that is, several hours. But this is not the end of the differences, because restarting the vacuum after a few hours gave a certain repeat of the effect, which again expired after a few hours and was cyclical.

The research aimed to keep the external (boundary) conditions used as comparable as possible. The same soil, irrigation, and temperature conditions were used, samples were taken from similar places in an identical manner, and so on.

The tested flysch soils consisted of dust silts with insertions of layers with chips and breccia of soft sedimentary rocks: shale, marl, sandstone, conglomerate, mudstone, and so on. Tests were limited to the weakest layers formed of dust silts, which were the main reason for landslide formation. The basic tests of strength parameters were performed for layers of two kinds of naturally formed silts representing the landslide soil mass: greyish-green and grey silt. Three shearing methods were applied:

(a) Borowicka—in the Direct Shear Test Apparatus,
(b) Kezdi—in the Direct Shear Test Apparatus,
(c) In the Triaxial Shear Test Apparatus.

On the basis of the complex and methodical tests conducted on the test stand demonstrated in Figures 5 and 6, a number of results were obtained, which are demonstrated in graphic form in Figures 7–12.

4.1. Comparative Studies of Intensity of Leaks from the TS

The shear strength of the cohesive soil (resistance to slide on the sliding surface) depends chiefly on the condition of the soil (the level of its liquidity index *LI*). Meanwhile, the soil condition depends on the ground water content in the soil. To determine the possibility of influencing the change in soil water content, the intensity of water removal from the soil with different methods was studied. The TS was studied subject to: (i) vacuum treatment, (ii) the ET process, and (iii) gravitational dewatering (with no external interference). Figure 7 compares the three methods of dewatering of the contact soil layer. On analyzing the obtained results, it can be seen that:

(a) the water outflow intensity from drainpipes during soil dewatering is highest by far with the electrokinetic method, especially in the early phase (the first three days).

(b) The results of outflow intensity studies of the vacuum method are comparable with those of the gravitational method. It must be mentioned, though, that after approximately 11 days the gravitational outflows stop, while those obtained by the vacuum method last much longer.

(c) soil dewatering using the gravitational and electrokinetic methods demonstrates constant outflows during the whole period of tests. Meanwhile, when using the vacuum method, outflows occur intensively for a short time (a few hours) and then stop. Starting the vacuum in cycles leads to renewed, intensive, short outflows.

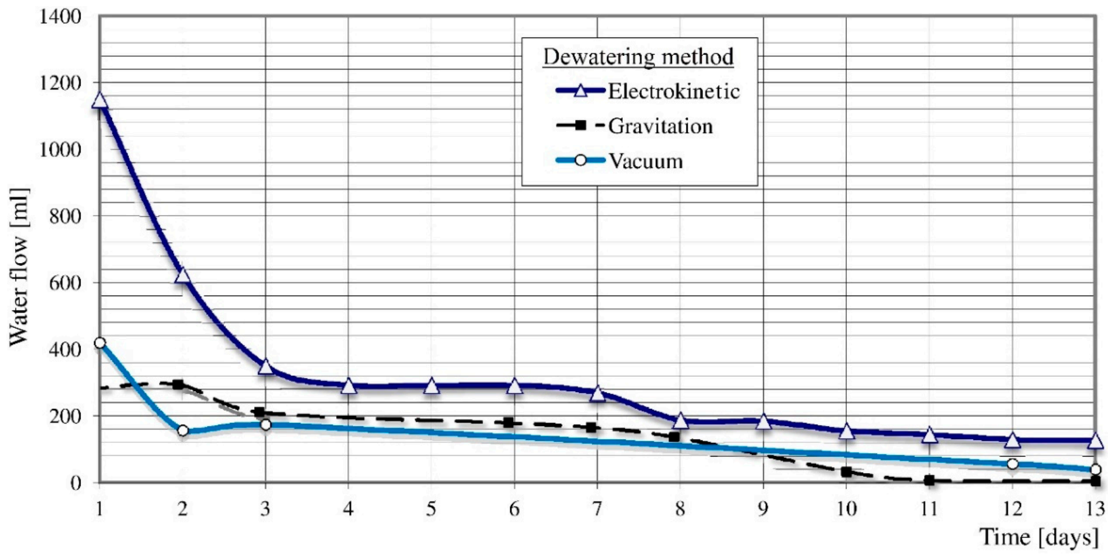


Figure 7. Outflow intensity diagram during the TS dewatering with the electrokinetic, vacuum, and gravitational methods.

4.2. Tests of Water Content Changes in the TS

The water outflow intensity from the soil does not present the complete picture of the change in the water content of the soil. Therefore, it was necessary to determine how the water content in the soil changes as time passes due to its outflow from the soil.

Figure 8 demonstrates the relationship between soil water content and time of dewatering for the three methods considered. The following observations result from the diagram presented here:

- using the electrokinetic method, a 4.6% reduction in the soil water content was obtained (during 14 days),
- at the same time, using the vacuum and gravitational methods, the soil water content decreased by 1.1%,
- using the gravitational method, the soil water content stabilized at a constant level. Meanwhile, with the remaining dewatering methods, especially the electrokinetic method, it decreased continually.

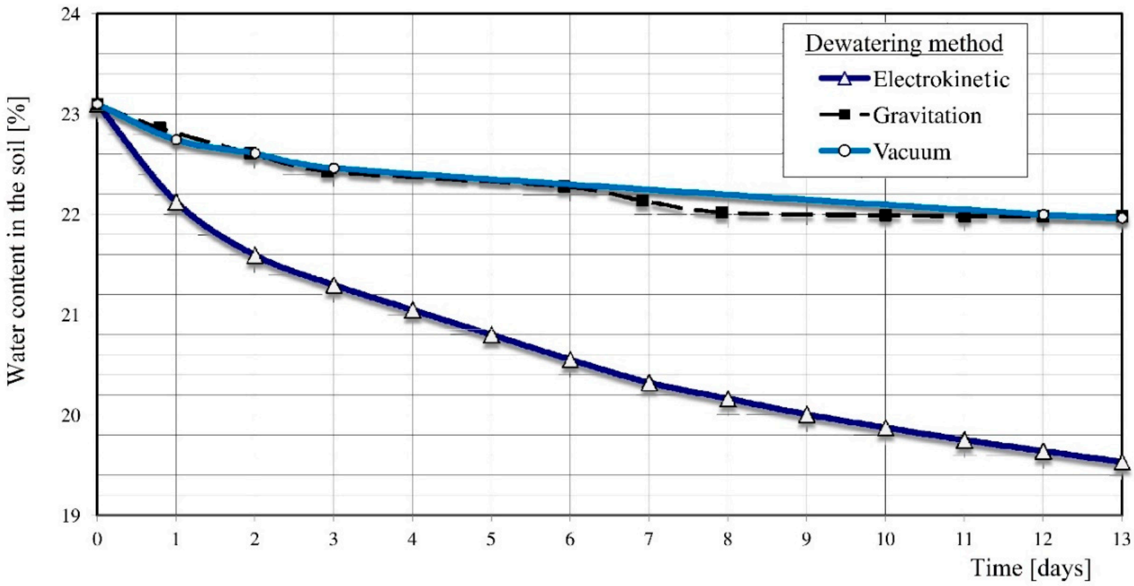


Figure 8. Diagram of change in water content during the TS dewatering with the electrokinetic, vacuum, and gravitational methods.

4.3. Determining the Relation Between the Risk Of Landslide Formation under the TS Condition and Its Water Content

In order to determine the physical and mechanical properties of the TS, its plasticity was determined by the liquidity index (*LI*). The liquidity index depends on the water content. This indicator determines the soil condition and has a decisive meaning with respect to the possibility of slide activation of the contact layer on the sliding surface. It was considered that the dependence of the possibility of slide on the soil condition was as follows:

- the soil in the hard plastic condition behaves in the way determined in Figure 3—there is a slight possibility of landslide occurrence, because this soil does not allow the mechanism demonstrated in Figure 3 to start,
- the soil in the plastic condition behaves in the way determined in Figure 3b—there may be a risk of landslide occurrence, which increases with the drop of the liquidity index,
- the soil in the soft plastic condition behaves in the way determined in Figure 3c—there is a high probability of landslide occurrence, because the mechanism of slide occurrence may be initiated easily.

Figure 9 presents the dependence of the plasticity level of the tested soil on its water content. From this diagram, it can be seen that the examined TS of the contact layer can be in the following conditions:

(a) hard plastic in the water content ranges below 26%,
(b) plastic in the water content ranges 26–34%,
(c) soft plastic in the water content ranges above 34%.

The range of soil water contents at which the soil condition passes from safe (with no risk of stability loss) to the hazardous state is approximately 8%. It can be accepted that only the application of the electrokinetic method during a period of approximately four weeks can provide stability or stabilization of an active landslide. This is due to the increase in the strength parameters of the contact layer. It results from the fact that diminishing the water content in the soil causes a drop in the liquidity index from soft plastic or plastic to hard plastic, and simultaneously there is an increase in the shear strength.

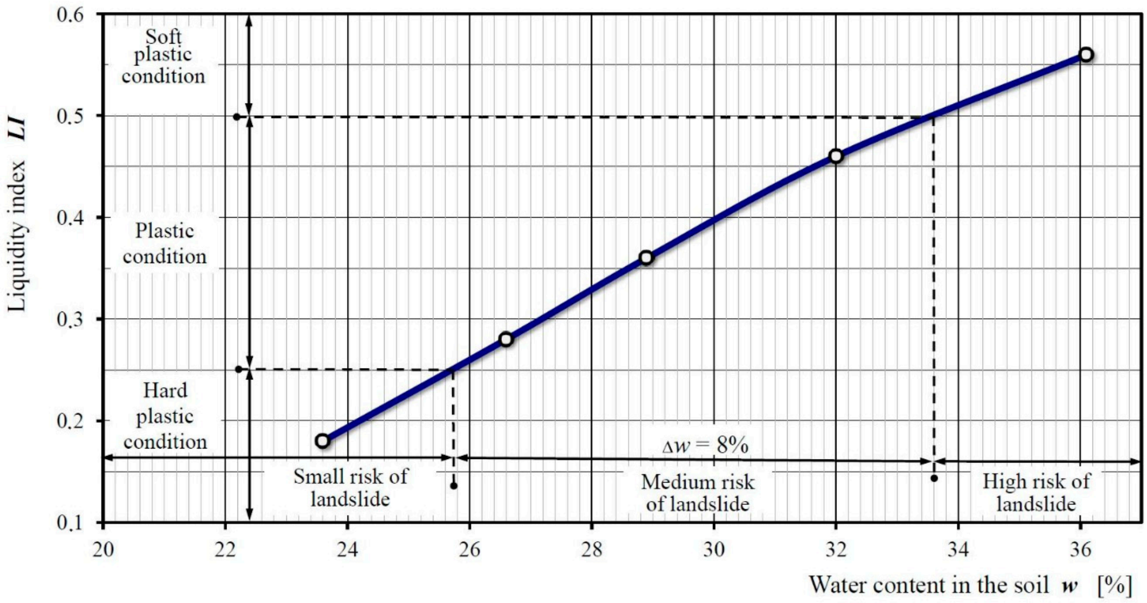


Figure 9. Diagram showing the relation between the TS state (liquidity index) in the soil contact layer and its water content.

4.4. Determination of the Influence of Water Pressure on the TS Strength Parameters

Ground water appears in the TS forming the landslide mass. The level of this water depends on atmospheric precipitation and its duration. Its presence may cause hydrostatic pressure which influences the pore pressure in the TS and changes the contact layer strength, especially on the sliding surface. Water may also exert hydrostatic pressure on the whole of the landslide block soil, regardless of its lift force. The influence of this factor was considered during studies controlling the pore pressure in the soil samples subject to shearing. Figure 10 presents the changes of Ψ (the effective angle of internal friction corresponding to the maximal border inclination of the sliding surfaces) depending on the hydrostatic pressure and depth of deposition of the slide layer.

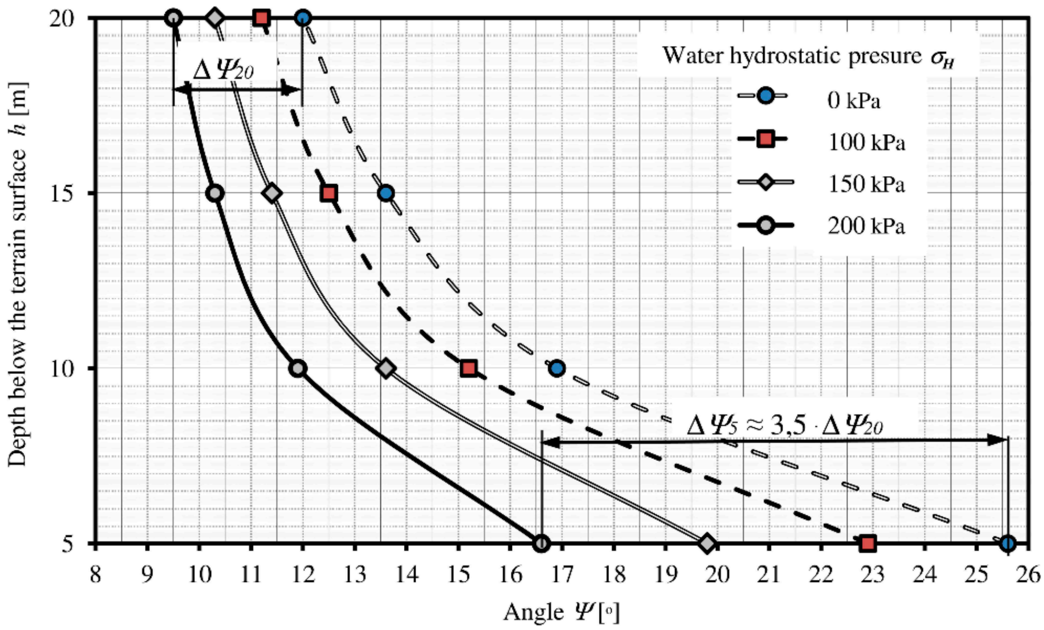


Figure 10. Dependency Ψ on the depth of deposition of the contact layer h for different values of the hydrostatic pressure σ_H.

On analyzing this diagram, it can be observed that:

- the value of Ψ (determined from Equations (4) and (5)) depends on the depth of location of the slide layer; that is, Ψ decreases with depth of deposition of the contact layer;
- with increases in the thickness of the TS layer, the hydrostatic pressure σ^H grows, exerting pressure on the underside of the block soil, leading to changes in the value of Ψ'?
- with depth and increase of the hydrostatic pressure σ^H we observe an increase of $\Delta\Psi$, namely growth of the effective angle of internal friction $\Delta\Psi$ (even 3,5 times—Figure 10).

4.5. Determining the Effectiveness of Growth of Soil Strength Parameters after Dewatering

The most important issue in the studies conducted was checking the effectiveness of the methods of soil dewatering on the increase in the soil shear strength. The conditions of free outflow of water from the soil caused by gravitation were compared with two methods of acceleration of this process: application of ET and vacuum treatment. The effective angle of internal friction ϕ' and effective cohesion c' are two soil parameters which are the best shear strength features. In noncohesive soils, $c' = 0$, and it is only possible to compare the parameter ϕ'. Meanwhile, in cohesive soils, both of these parameters have values that are different from zero and their increases differ considerably from one another. It is more convenient in this case to compare the effective angle of internal friction for the border inclination of sliding surfaces calculated according to Equations (4) and (5).

Figure 11 presents diagrams characterizing the angles Ψ_1, Ψ_2, Ψ_3, and Ψ_4, (effective friction angles, corresponding to the maximal border inclination of sliding surfaces, determined at normal stresses equal to σ_1 = 100, 200, 300, and 400 kPa, respectively) for the vacuum and electrokinetic methods. It presents the results of studies conducted for the contact layer, which show that:

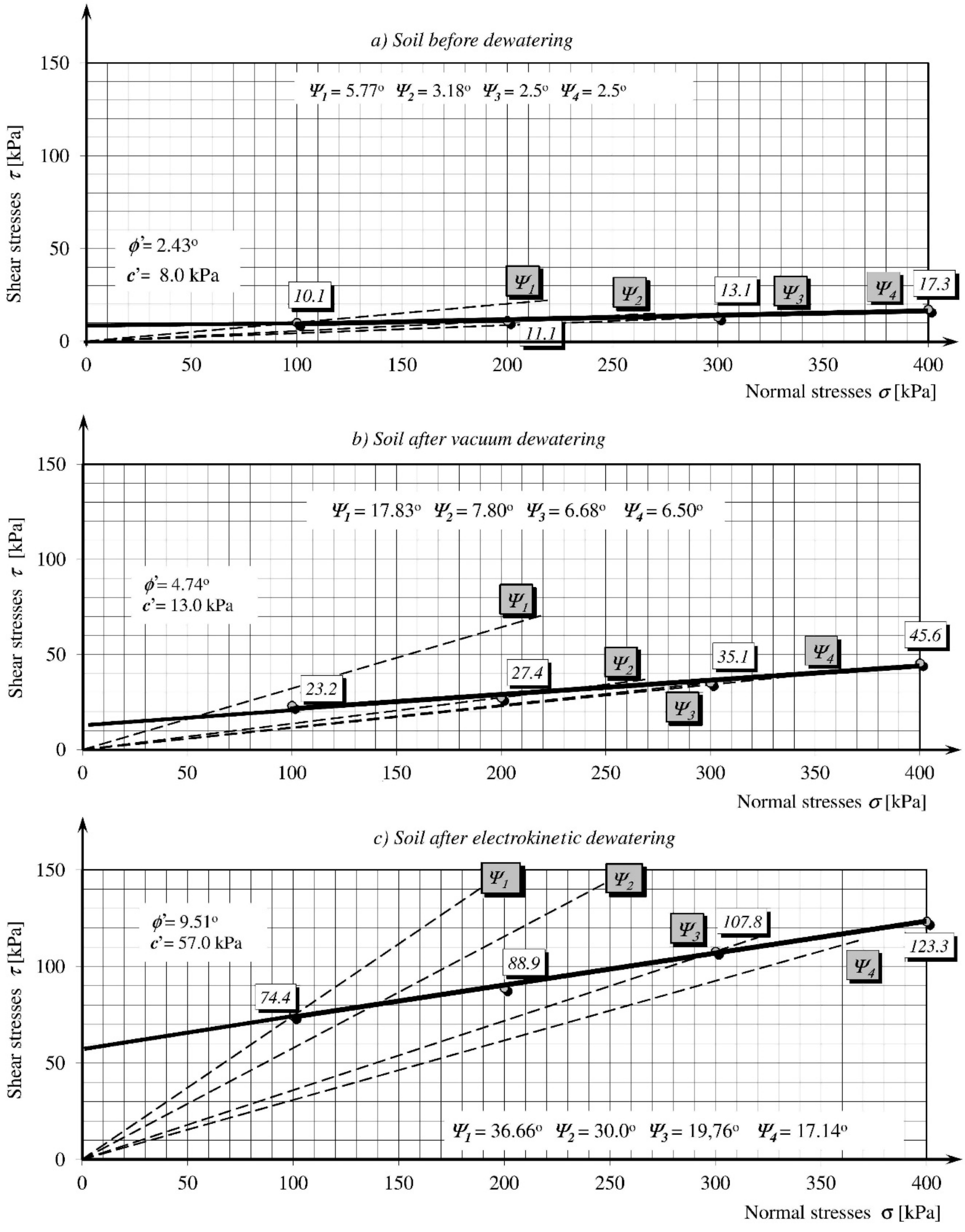
- in the case of both methods, in the range of the internal friction effective angle ϕ' and cohesion c', decisive increases of these parameters take place for the samples from the contact layer,
- the effective soil parameters after dewatering (ϕ'_r, c', and Ψ_1) increase substantially with respect to the soil before dewatering (ϕ'°, c'°, and $\Psi_1{}^{\circ}$). Comparing the values $\Psi_1{}^{\circ}$ and Ψ_1, it can be seen that the internal friction effective angles, corresponding to the maximal border inclination of the sliding surfaces, increase approximately three times with the vacuum method and approximately six times with the electrokinetic method (Tables 1 and 2).

Table 1. The effect of increases in parameters caused by vacuum dewatering.

Parameter	TS Soil Parameter		Increase [%]
	Before Dewatering	After Dewatering	
c' [kPa]	8.0	13.0	62.5
ϕ' [°]	2.43	4.73	94.7
Ψ_1 [°]	5.77	17.83	209.0

Table 2. The effect of increases in parameters caused by electrokinetic dewatering.

Parameter	TS Soil Parameter		Increase [%]
	Before Dewatering	After Dewatering	
c' [kPa]	8.0	57.0	612.5
ϕ' [°]	2.43	9.51	291.4
Ψ_1 [°]	5.77	36.66	535.4



Ψ_1, Ψ_2, Ψ_3, Ψ_4, - effective internal friction angles for boundary inclination of slide surfaces determined at total normal stresses: σ_1 =100 kPa, 200 kPa, 300 kPa, 400 kPa.

Figure 11. Diagram of the strength parameters of the contact layer soil before and after conducting dewatering by three methods (gravitational, vacuum, and electrokinetic).

4.6. Comparison of the Influence of The Selected Method in the TS Study on the Final Results

Selection of the correct method of determining the shear strength of cohesive soils depends on the specificity of the natural conditions in which the shearing occurs. It can be assumed in advance that the Borowicka method should map the real conditions of soil strength on the sliding surface in the best way. However, in order to determine how crucial the differences in results obtained with different methods are in tests of the sliding surface, the same tests were conducted simultaneously with the Kezdi method.

The comparison of the two methods is presented in Figure 12. It demonstrates the relation of the effective internal friction angle ϕ', cohesion c', and angle Ψ determined according to the two methods, Borowicka and Kezdi, for different values of the liquidity index *LI*.

From this comparison, it is found that:

- for *LI* = 0.5–0.25, that is, w = 26.0–33.6%, covering the soil plasticity condition (medium risk of landslide), the largest differences between the two methods occur,
- the results obtained by the Kezdi method with respect to the angle Ψ are 2°–6° higher than those obtained by the Borowicki method,
- the Borowicka method is safer for analyzing the sliding surface of the contact layer in the direct soil shearing box apparatus,
- in the examined soil, the Borowicka method gives safer results than the Kezdi method in the range of soil water contents of 24–35%.

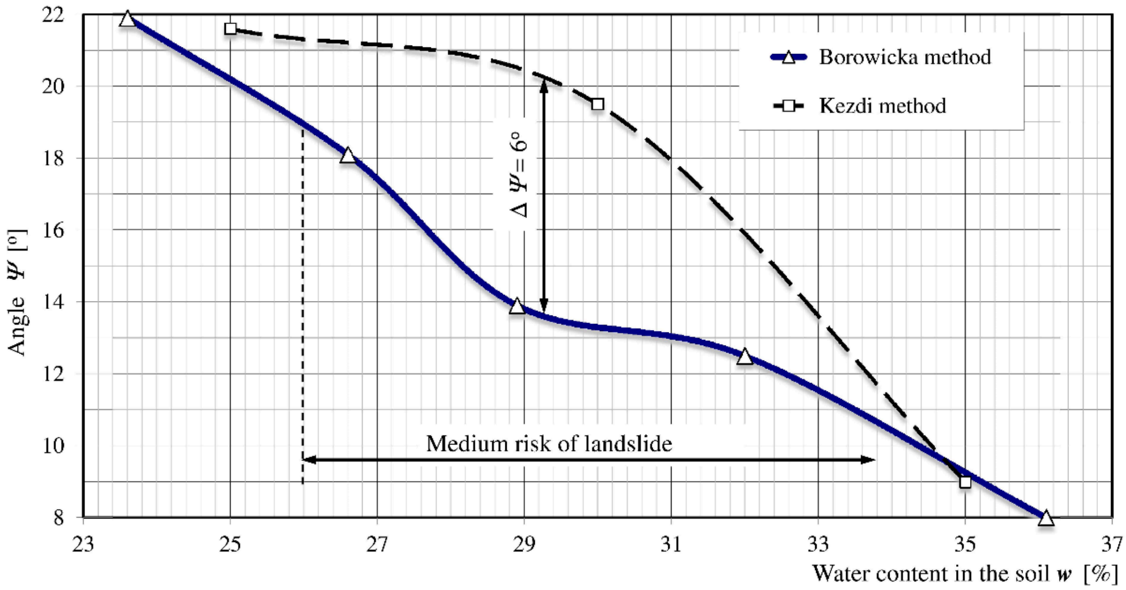


Figure 12. The inclination angle Ψ for the Borowicka and Kezdi methods at different water contents in TS forming the contact layer.

5. Conclusions

The experiments conducted concerned a comparison of the effectiveness of the application of three selected methods (electrokinetic, vacuum, and gravity treatments) in practical and technical conditions of their application. The key aim of this research was to answer to the question of how effective these methods are, which process is more powerful for practical applications for drainage and stabilization of an existing landslide, and how quickly could technically acceptable results be achieved in conditions of landslide stabilization.

The executed research focused on the practical application of these methods in natural conditions and did not preclude their use together.

Generally, it should be stated that the nature and manner of conducting the research resulted from the need to ensure constant and identical external conditions. The conditions could only be controlled in a built model stand under laboratory conditions. It would be difficult or even impossible to make tests under a real terrain condition or based on standard laboratory tests.

Therefore, the model test stand reflected the real size (on a 1:1 scale) of the fragment of the contact layer at the interface of the soil layers constituting the slip plane. This tested part is a special kind of soil because it decides the stability of whole landslide body independently of its upper layering. So, this thin layer of soil sometimes is most important for the whole of a massive slope body because the condition of this layer decides it stability. The strength of this layer is mainly influenced by its water content, so dewatering by using ET and vacuum treatment could be a good solution to stabilize the landslide body.

The analysis, field works, and model laboratory tests conducted on the flysch TS allowed for the following general conclusions to be drawn:

- The condition of the contact layer soil (forming the sliding surfaces) is decisive for the initiation of the landslide. The water content in the contact layer soil has a large influence on the condition of the soil (defined by the liquidity index). Reducing the soil water content causes an increase in strength of the soil wall and an increase in the stability of the landslide mass. Thus, controlling the soil water content is crucial for gaining control over landslides in cohesive soils.
- The analysis of soils forming the slide zone of the contact layer conducted by the Borowicka method provides safer results than the Kezdi method, especially for soils in plastic condition.
- The range of change of water content in the examined TS, wherein the soil condition passes from safe (small risk of stability loss) to the hazardous state, is approximately 8%. The electrokinetic method diminishes the water content in the soil by approximately 4.6% within two weeks. Therefore, it can be assumed (taking into account the recorded stability of the dewatering effect) that application of this method during a period of approximately four weeks will provide scarp stability or stabilization of an active landslide by correction of the physical and mechanical parameters of the contact layer. Obtaining such a state of the soil is possible provided that no water can flow to the contact layer soil. This can be achieved by correct execution of the intake and draining of rainwater to outside of the landslide.
- Although the vacuum method demonstrates ability to dewater the soil comparable to the gravitational outflow, it is far less effective than the electrokinetic method. Therefore, it can be recommended only as the supporting method, especially at the soil injection.
- Variability of the effective internal friction angle corresponding to the maximal border inclination of sliding surfaces Ψ clearly depends on the depth at which the contact layer occurs, normal stresses in the soil, and hydrostatic pressure occurring at the level of the slide surface. With increases in depth and the value of hydrostatic pressure acting on the landslide block soil, the value of Ψ diminishes.
- Applications of the electrokinetic or electrokinetic-vacuum method of dewatering the soil are effective. They lead to beneficial stabilization processes and may be used effectively for stabilization of landslides. The condition of their application is effective intake of rainwater at a level that ensures safe control of the ground water level during periods of precipitation.
- In cases of the need for less important landslide counter reacting, protective works may be limited to efficient intake of surface water and outflows of depth water as well as gravitational dewatering. It is also possible to apply a combination of the methods discussed above, selected with reference to the terrain conditions and geological structure of the area analyzed with respect to stability.

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References

1. Horvitz, W. The theory of electrokinetic phenomena. *J. Chem. Educ.* **1939**, *16*, 519–535. [CrossRef]
2. Casagrande, L. Electro-osmosis in soils. *Geotechnique* **1949**, *1*, 159–177. [CrossRef]
3. Casagrande, L.; Longhney, R.W.; Matich, A.J. Elektro-Osmotic Stabilization of a High Slope. In Proceedings of the 5th Intnational Conference on Soli Mechanics and Foundation Engineering, Paris, Franch, 17–22 July 1961; Volume 1.
4. Ukleja, K. *Electroosmotic Drying of Slime Consistence Wastes*; Industrial Enviromental Research Laboratory, US EPA: Cincinnati, OH, USA, 1972; p. 210.
5. Lo, K.Y.; Ho, K.S.; Inculet, I.I. Field test of electroosmotic strengthening of soft sensitive clay. *Can. Geotech. J.* **1991**, *28*, 74–83. [CrossRef]
6. Lo, K.Y.; Inculet, I.I.; Ho, K.S. Electroosmotic strengthening of soft sensitive clay. *Can. Geotech. J.* **1991**, *28*, 62–73. [CrossRef]
7. Hong, H.P.; Shang, J.Q. Probabilistic analysis of consolidation with prefabricated vertical drains for soil improvement. *Can. Geotech. J.* **1998**, *35*, 666–677. [CrossRef]
8. Chen, J.L.; Murdoch, L. Effects of electroosmosis on natural soil: Field test. *J. Geotech. Geoenviron. Eng.* **1999**, *125*, 1090–1098. [CrossRef]
9. Mohamedelhassan, E.; Shang, J.Q. Effects of electrode materials and current intermittence in electro-osmosis. *Ground. Improv.* **2001**, *5*, 3–11. [CrossRef]
10. Glendinning, S.; Jones, C.J.; Pugh, R.C. Reinforced soil using cohesive fill and electrokinetic geosynthetics. *Int. J. Geomechanics* **2005**, *5*, 138–146. [CrossRef]
11. Reddy, K.R.; Urbanek, A.; Khodadoust, A.P. Electroosmotic dewatering of dredged sediments: Bench-scale investigation. *J. Environ. Manag.* **2006**, *78*, 200–208. [CrossRef]
12. Su, J.Q.; Wang, Z. The two-dimensional consolidation theory of electro-osmosis. *Geotechnique* **2003**, *53*, 759–763. [CrossRef]
13. Gabrieli, L.; Alshawabkeh, A.N. Influence of boundary conditions on transient excess pore pressure during electrokinetic applications in soils. *J. Appl. Electrochem.* **2010**, *40*, 1113–1121. [CrossRef]
14. Deng, A.; Zhou, Y. A Piecewise-Linear Numerical Model for One-Dimensional Electroosmosis Consolidation. In Proceedings of the International Conference on Ground Improvement (ICGI 2012), Wollongong, Australia, 30 October–2 November 2012; pp. 1369–1375.
15. Zhou, Y.; Deng, A.; Wang, C. Finite-difference model for one-dimensional electro-osmotic consolidation. *Comput. Geotech.* **2013**, *54*, 152–165. [CrossRef]
16. Al-Hamdan, A.Z.; Reddy, K.R. Electrokinetic remediation modelling incorporating geochemical effects. *J. Geotech. Geoenviron. Eng.* **2008**, *134*, 91–105. [CrossRef]
17. Gargano, S.; Lirer, S.; Flora, A. Analysis of the coupled electro-osmotic and mechanical consolidation in clayey soils. *Proc. Inst. Civ. Eng. Ground Improv.* **2019**, *172*, 146–157. [CrossRef]
18. Gargano, S.; Lirer, S.; Flora, A. Mechanical and Physical Effects of Electroosmotic Dewatering of Clayey Soils. In *National Conference of the Researchers of Geotechnical Engineering*; Calvetti, F., Ed.; Springer: Cham, Switzerland, 2020; pp. 387–396. [CrossRef]
19. Shang, J.Q.; Tang, M.; Miao, Z. Vacuum preloading consolidation of reclaimed land: A case study. *Can. Geotech. J.* **1998**, *35*, 740–749. [CrossRef]
20. Deng, A.; Xu, S. Consolidating Dredge Soil by Combining Vacuum and Dynamic Compaction Effort. In *Ground Improvement and Geosynthetics*; American Society of Civil Engineers: Reston, VA, USA, 2010; pp. 113–118.
21. Li, L.H.; Wang, Q.; Wang, J.; Wang, N. Analysis of stress path soils deformation under the vacuum drainage preloading. *J. Eng. Geol.* **2001**, *9*, 170–173.
22. Li, L.H.; Wang, Q.; Wang, N.X.; Wang, J.P. Vacuum dewatering and horizontal drainage blankets: A method for layered soil reclamation. *Bull. Eng. Geol. Environ.* **2009**, *68*, 277–285. [CrossRef]
23. Wu, H.; Hu, L. Theoretical Analysis and Numerical Simulation of Vacuum Preloading in Combination with Electro-osmosis Consolidation. In Proceedings of the Conference Paper Geo-Frontiers 2011, Dallas, TX, USA, 13–16 March 2011.
24. Lian-Heng, Z.; Jingyuan, C.; Yingbin, Z.; Qiang, L. Effect of hydraulic distribution on the stability of a plane slide rock slope under the nonlinear Barton-Bandis failure criterion. *Geomech. Eng.* **2015**, *8*, 391–414.

25. Jian, J.; Hong-Jian, L. Sensitivity-based reliability analysis of earth slopes using finite element method. *Geomech. Eng.* **2014**, *6*, 545–560.
26. Kuangmin, W.; Sheng, Z. Application of an elastoplastic model to predict behaviors of Concrete-Faced Rock-fill Dam under complex loading conditions. *J. Civ. Eng. Manag.* **2015**, *21*, 854–865.
27. Jiuping, X.; Cuiying, F. Two-stage based dynamic earth-rock transportation assignment problem under fuzzy random environment to earth-rock dam construction. *J. Civ. Eng. Manag.* **2015**, *21*, 775–797.
28. Poisel, R.; Angerer, H.; Pöllinger, M.; Kalcher, T.; Kittl, H. Mechanics and velocity of the Lärchberg–Galgenwald landslide (Austria). *Eng. Geol.* **2009**, *109*, 57–66. [CrossRef]
29. Al-Homoud, A.S.; Tal, A.B.; Taqieddin, S.A. A comparative study of slope stability methods and mitigative design of a highway embankment landslide with a potential for deep seated sliding. *Eng. Geol.* **1997**, *47*, 157–173. [CrossRef]
30. Salcedo, D.A. Behavior of a landslide prior to inducing a viaduct failure, Caracas–La Guaira highway, Venezuela. *Eng. Geol.* **2009**, *109*, 16–30. [CrossRef]
31. Wilun, Z. *Outline of the Geotechnics*; Wydawnictwo Komunikacji i Lacznosci: Warsaw, Poland, 1982; pp. 194–199.
32. Borowicka, H. *Uber Die Scherfestigkeit Bindiger Boden*; Mitt.des Instituts fur Grundbau und Bodenmechanik: Wien, Austria, 1961.
33. Kezdi, A. *Erddrucktheorien*; Springer: Berlin/Heidelberg, Germany, 1962.
34. Ukleja, J.; Ukleja, K. Increasing of Soil Slide Stabilization Using Forced Dewatering by Vacuum and Electrokinetic Phenomena. In Proceedings of the Conference on Geotechnic and Special Construction, Krakow, Poland, 12 May 2006; pp. 519–535.