Groundwater regime associated with slope stability in Champlain clay deposits

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Received October 17, 1978
Accepted September 19, 1979

Slope stability analyses in terms of effective stresses are most often based on hypothetical conditions of pore pressure. It is generally assumed that the flow occurs parallel to the slope or even that the conditions are hydrostatic. In fact, *in situ* measurements tend to show that the real situation could significantly deviate from these approximations due to geologic conditions. The influence of various geometric and stratigraphic factors on the groundwater regime and on the stability of slopes was studied with the finite-element method. To illustrate the parametric study, experimental evaluations of the flow patterns are presented at four sites. The stratigraphy and permeability measurements combined with the finite-element method enabled a complete flow net to be drawn and although some hypotheses had to be formulated with regards to the underlying aquifer recharge or permeability anisotropy, reasonable agreement was found between simulated and measured piezometric heads.

La justesse des analyses de stabilité en contraintes effectives des pentes d'argile de la mer Champlain est souvent atténuée par les hypothèses qui sont faites quant à la distribution des pressions interstitielles; ainsi en l'absence de mesures piézométriques, on suppose que l'écoulement se fait parallèlement à la pente ou, de façon plus pessimiste, que les conditions sont hydrostatiques.

En réalité, des mesures *in situ* ont démontré que ces approximations pouvaient s'avérer fausses, et qu'on pouvait relier ces écarts aux conditions géologiques. On a alors entrepris une étude paramétrique à l'aide de la méthode des éléments finis et on a mis en relief l'influence prépondérante sur le régime des eaux souterraines et sur la stabilité des pentes, de couches plus perméables telles que till ou argile fissurée, adjacentes au dépôt d'argile.

En deuxième partie, on présente une étude de quatre cas représentatifs d'écoulement en pente argileuse. La stratigraphie détaillée et les mesures de perméabilité combinées à l'utilisation du programme d'éléments finis ont permis de tracer le réseau d'écoulement complet au voisinage de ces pentes et malgré les hypothèses faites sur la recharge des aquifères sous-jacents à l'argile, ou sur les rapports d'anisotropie de perméabilité, les charges piézométriques calculées concordent bien avec celles qui ont été mesurées.

Can. Geotech. J., **17**, 44–53 (1980)

Introduction

Since the early sixties, soil mechanics has progressed significantly in the evaluation of the stability of natural slopes. It is more and more accepted that such slopes should be analysed in terms of effective stresses. Much attention has been devoted to determining the effective strength parameters of the Champlain clay that should be used in the analysis (Lo and Lee 1974; Lefebvre and La Rochelle 1974; Mitchell 1975). The pore-pressure distribution necessary for the analysis is, however, most often based on rather simple assumptions. The flow is frequently assumed to be parallel to the slope or, at worst, the pore pressures are calculated as being under hydrostatic conditions.

Because of geometry and local geology, the flow pattern can differ significantly from the simple models mentioned above. La Rochelle *et al.* (1970) presented some examples of an important upward gradi[ent] existing at the toe of a slope that was at that ti[me] related to the configuration of the underlying be[d]rock. More recently, Hodge and Freeze (1977), a[fter] detailing a modelling technique based on the fi[nite-]element method to describe the groundwater mo[ve]ment on a regional basis, have pointed out [the] influence of the entire geological environment (hy[]draulic conductivity contrasts and anisotropy) [on] the groundwater flow system with an emphasis on the stability of rock slopes.

The purpose of this paper is to show that, du[e to] the geological environment of the Champlain c[lay,] the movement of groundwater in the vicinity o[f] slopes results in a pore-pressure distribution [that] could be very different from the simple assump[tions] mentioned above. The first part of the paper [illus]trates the influence of various factors on the p[ore-]pressure distribution using a modelling tech[nique] based on the finite-element method. A param[etric] slope stability analysis translates the effect of [...]

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pressure distribution in terms of the variation of the factor of safety against failure. The second part presents field data obtained at four sites in the St. Lawrence valley to support the theoretical findings.

Formation of Clay Deposits

The Champlain clay deposits can be considered as a relatively thick impermeable stratum always bounded at its lower and upper parts by two more pervious layers. At the bottom, the marine clay overlies either a till sheet or a fissured bedrock or any granular material at least 100 times more permeable. On top of the clay, upon isostatic uplift, a drainage pattern was developed by the regression of the sea as alluvial sands were often deposited. Where no sandy layers overlie the clay stratum, the original upper portion of the clay was desiccated, oxydized, and fissured to a variable extent resulting in an overall hydraulic conductivity as large as 10^{-5} cm/s (Lafleur 1978). Another point is worth consideration with regard to clay deposition: since the conditions of sedimentation varied with time, the clays can be laminated with sand or silt seams that introduce the equivalent of a permeability anisotropy.

Influence of Various Factors on Pore-pressure Distribution

Modelling Technique

The finite-element method (FEM) offered the most versatile solution for drawing the flow nets associated with different geologic and geometric conditions. The method described in detail by Neuman and Witherspoon (1970) easily evaluates the hydraulic head at every point in a flow region involving rather complex geometry and boundary conditions and determines the position of the phreatic surface in conditions of infiltration or evaporation.

The computer program FREESURF developed at Berkeley, California, and based on the Neuman and Witherspoon method (1970) was used to investigate two-dimensional seepage in an unconfined flow region. The flow region was subdivided into 212 quadrilateral elements. The input data consisted of the position of each nodal point, hydraulic conductivities in the principal directions, the first trial position of the phreatic surface, the vertical infiltration rate, and the boundary conditions. By iterative procedure, the heads were calculated at each nodal point and the program shifted the position of the phreatic surface until the error between the assumed and the calculated position was within acceptable limits. The total and the pressure head computed for each nodal point by FREESURF were subsequently processed by another program so that equipotential and equi pressure lines could be drawn by a tracing table.

Factors and Assumptions Considered in the Analyse

The parametric study was undertaken to evaluat the relative influence of different factors on the flov regime associated with slopes and 22 models wer finally considered in the analysis. The followin factors were varied in accordance with the physica context of the Champlain Sea area: infiltration rate vertical position of the lower aquifer with respect t the toe of the slope; permeability anisotropy; an geometry (extent and shape) of the drainage basin

The definitions and symbols are given in Fig. 1 Some general assumptions were made with regard t boundary conditions, slope dimensions, and per meability distribution: the calculations were mad for two-dimensional cases with uniform hydrauli conductivity in each zone; even though the lowe aquifer can in fact be more permeable than the cla by several orders of magnitude, the hydraulic con ductivity ratio was assumed to be less than 100. Th profile corresponds to a typical stable Champlai clay slope: angle, 18°; thickness of the upper per meable clay crust, 2 m; and height, 15 m. Finally, th upstream and downstream boundaries correspondin respectively to the water divide and thalweg line were implicitly impervious boundaries since the constituted with the bottom line the extreme flow lin of this closed system; on the other hand, if th adjacent drainage basins are symmetrical, thes boundaries are vertical as assumed in this parametri study.

Existence and Influence of a Superficial Layer

Since a permeable layer was found to be invariabl present at the top of the clay deposits, the infiltratio capacity of the soil was presumed to be influenced b its permeability or by the rates of infiltration. Th position of the water table and the flow net in thi layer were studied and it was found that when th infiltration rate was taken equal to the average annu precipitation rate, the water table was brought to th ground surface (implying runoff) and flow occurre parallel to the slope; on the other hand, with a muc lower rate (100 times less) the phreatic surface wa lowered, but flow still occurred parallel to the slop in the upper aquifer. Although these results did n take into account the effect of evapo–transpiration o infiltration rates and decreasing hydraulic conduc tivity with depth in the upper aquifer, they pointe out firstly that the assumption of water level at th ground surface during periods of high infiltratio can be justified, and for this reason the other facto were studied assuming no upper aquifer and wat

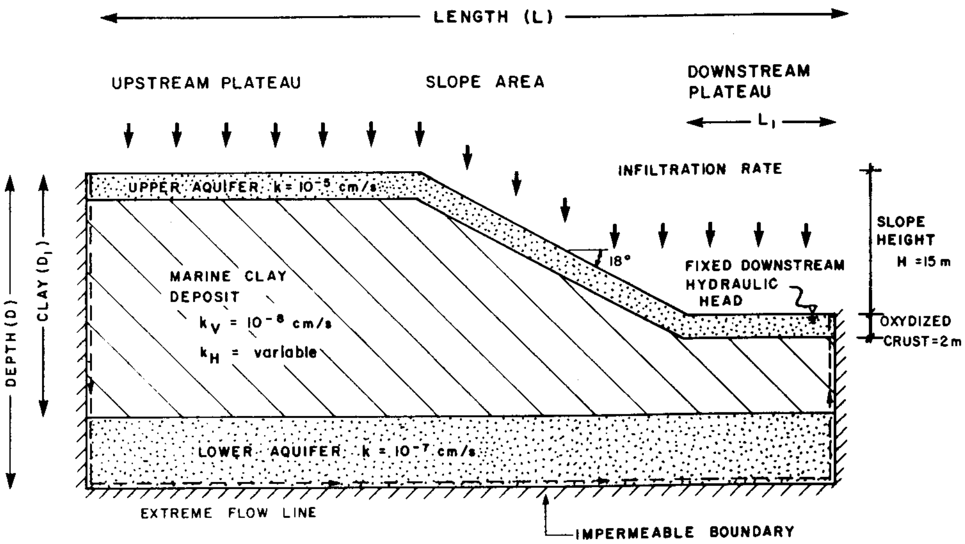


FIG. 1. Parametric study: definition of variables and assumptions.

level at the ground surface for simplicity of calculation. Secondly, it was shown that the upper aquifer can result in flow parallel to the slope, a justifiable assumption when analysing shallow landslides in superficial clay.

Influence of a Lower Aquifer

In relation to deep failures, the parametric study of the groundwater regime surrounding slopes shows that the lower aquifer has a maximal influence on the distribution of pore pressures in the intact clay, and that this distribution can be altered significantly from the so-called hydrostatic conditions. The resulting flow nets are shown in Fig. 2 for different positions of the lower aquifer. The intensity of the upward gradients in the lower part of the slope can be related directly to the closeness of the equipotentials; these results are presented differently in Fig. 3 where the vertical gradients on three axes have been plotted as a function of the position of the aquifer. The upward gradients at the toe of the slope, which are of interest for stability computations, show different patterns if the lower limit of the clay layer is below or above the toe level: above, the entire deposit is underdrained, but below, the clay is submitted to artesian pressure and the upward gradient can be greatly in excess of the critical value of 0.6 (assuming a soil weighing 16 kN/m^3, this implies that the effective stress is zero and that the shear strength is reduced to its cohesion component).

Influence of Permeability Anisotropy

In Fig. 4 the absolute value of the gradients is seen

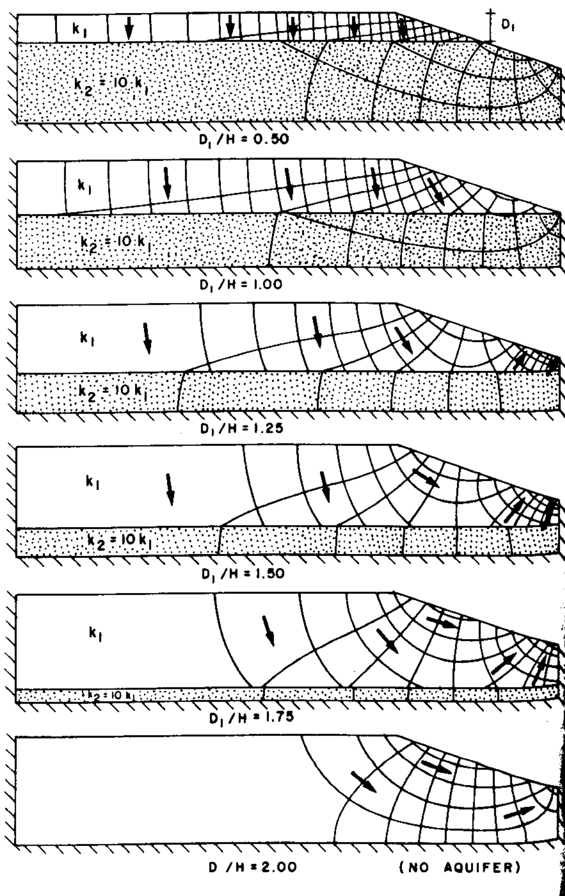
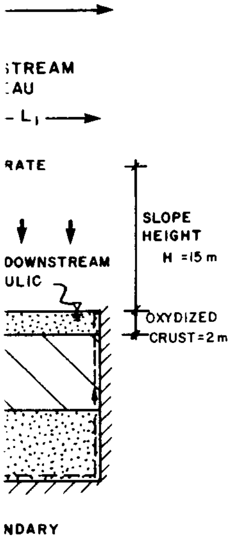


FIG. 2. Flow nets: influence of position of lower aquifer



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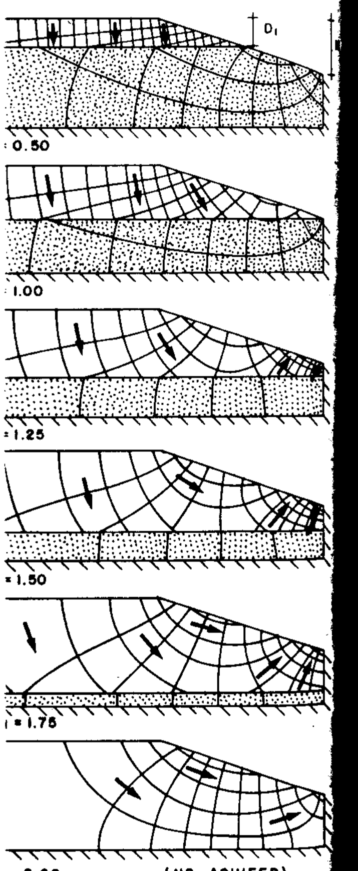

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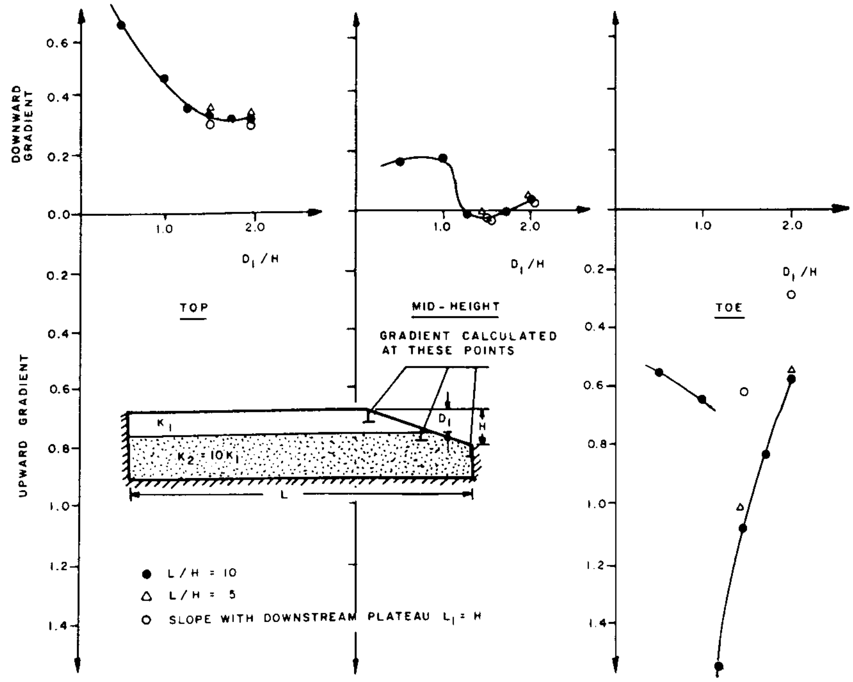


FIG. 3. Influence of the position of lower aquifer on hydraulic gradient.

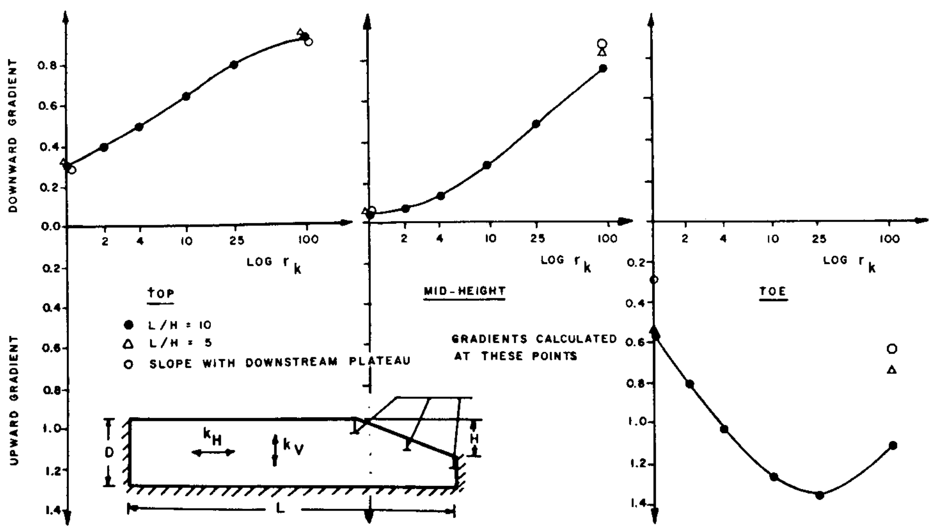


FIG. 4. Influence of anisotropy ($r_k = k_H/k_V$) on hydraulic gradients.

to increase approximately with the logarithm of the anisotropy ratio (r_k) up to a ratio of 25.

Influence of Geometry

The influence of geometry can readily be observed in Fig. 3 for the slope with a lower aquifer and in Fig. 4 for the anisotropic clay: the length of the basin and the presence of a downstream plateau have no perceptible influence on the downward gradients at the top and midheight of the slope. On the other hand, both factors can decrease the upward gradient at the toe of the slope by 50% provided that the length of the downstream plateau $L_1 \geq H$, and the length of the basin $L \leq 5H$, where H is the slope height.

Significance of Pore-Pressure Distribution in Slope Stability Analysis

To assess the degree of influence of these factors, stability analyses were performed for a typical slope

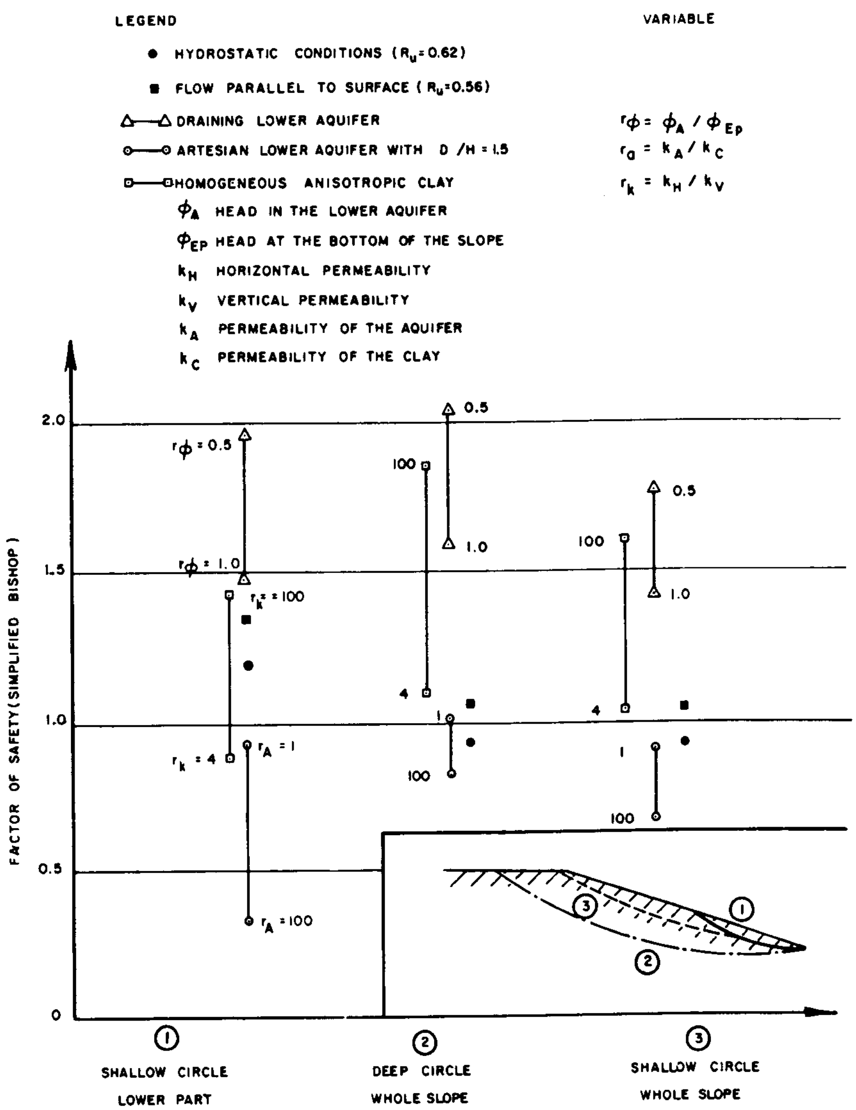
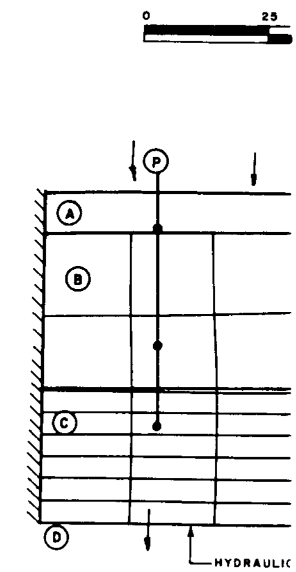


FIG. 5. Influence of groundwater regime on factor of safety.

aving the following characteristics: $c' = 7$ kPa; $\phi' = 31°$; $\gamma = 16$ kN/m³; phreatic surface at ground evel; and no tension cracks. The stability analyses vere done by the simplified Bishop method using a omputer program in which the positions of equipressure lines could be entered directly. Three specified slip circles were chosen according to various ossible locations of failure surface: ① shallow ircle involving the toe of the slope; ② deep circle nvolving the whole slope; and ③ shallow circle nvolving the whole slope.

The results are shown in Fig. 5 for these three ircles; the different groundwater conditions caused he factor of safety to vary between 0.3 and 2.0. This scatter for a unique slope with varying groundwa[ter] conditions is related to whether the lower aquifer [is] drained or artesian: a drained aquifer with ϕ_a/ϕ_{ep} [=] 0.5 gives a factor of safety of 2. If this same aquife[r is] artesian and the ratio of the coefficient of permeab[il]ity of the aquifer to that of the clay is 100, the fac[tor] of safety is shown to vary between 0.3 and [...] Finally, the overall effect of assuming permeabi[lity] anisotropy is a general increase in the factor of saf[ety] with respect to the isotropic medium. The values o[f] obtained with the usual assumptions for po[re] pressure distributions (hydrostatic conditions or fl[ow] parallel to surface) are close to unity.



Comparison with Observed

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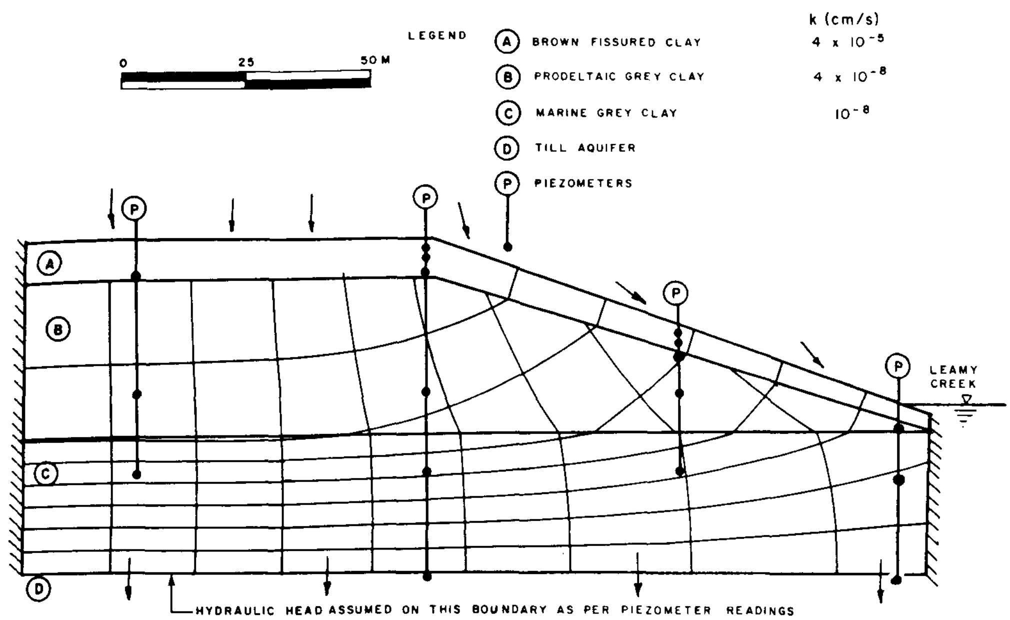


FIG. 6. Flow net: Hull.

Comparison with Observed Flow Patterns

The four sites have been selected to represent a wide variation of conditions. The clay deposits are underdrained at two sites: at St-Urbain the clay is drained above the toe of the slope, whereas at Hull it is thicker and drained to an aquifer lying much below the toe of the slope. The St-Ambroise and Nicolet sites involve clay deposits fed by artesian aquifers with different geometries. The Nicolet clay deposit is large in extent compared with that at St-Ambroise, which involves a narrow clay tongue lying between rock valley walls. Anisotropy effects have been investigated at St-Urbain.

The fieldwork generally consisted of a detailed stratigraphic investigation with tube sampling, visual inspection of exposed faces of the deposits, installation of piezometer tips on vertical axes near the slope, and permeability tests in auger-holes and open-tube piezometers. Measurements of hydraulic heads in the slope area were obtained at time intervals close enough to register possible fluctuations. A special surface piezometer was developed to record the maximum position of the water table in the upper clay crust during springtime. Finally, the stratigraphy, geometry, permeability evaluation, and measured boundary conditions were combined in a finite element analysis to draw a flow net at each site. Where our knowledge of the permeability coefficients and of the boundary conditions was accurate, a reasonable agreement was observed between measured and calculated piezometric heads. However, at St-Urbain and Nicolet some assumptions or adjustments had to be made with regard to the permeability anisotropy ratio and boundary conditions, so that both pressure distributions would become equal.

Site No. 1—Hull

This site is located in the Leamy Creek valley in the north end of the city. The valley is symmetrical and the plateau is fairly horizontal. The idealized geometry, the location of piezometers, and the stratigraphy are given in Fig. 6. The sedimentary deposit consists of the following four zones.

A. *Brown fissured and oxydized clay crust:* Highly fractured and containing roots for the first 2–3 m. Overall *in situ* permeability measurements by different methods gave a value of $k = 2\text{–}30 \times 10^{-5}$ cm/s.

B. *Grey silty clay:* This material is believed to correspond to the prodeltaïc clay described by Fransham and Gadd (1977). Permeability measured in open porous stone piezometers was $k = 4 \times 10^{-8}$ cm/s.

C. *Grey silty marine clay:* Some traces of organic matter appeared in this horizon. Piezometric measurements indicate that this clay is slightly less permeable than the one above and a value of 10^{-8} cm/s was assumed for this stratum.

D. *Till:* This aquifer has been identified as a silty sand and gravel and, being drained towards the Gatineau River flowing 1 km east of the site at a

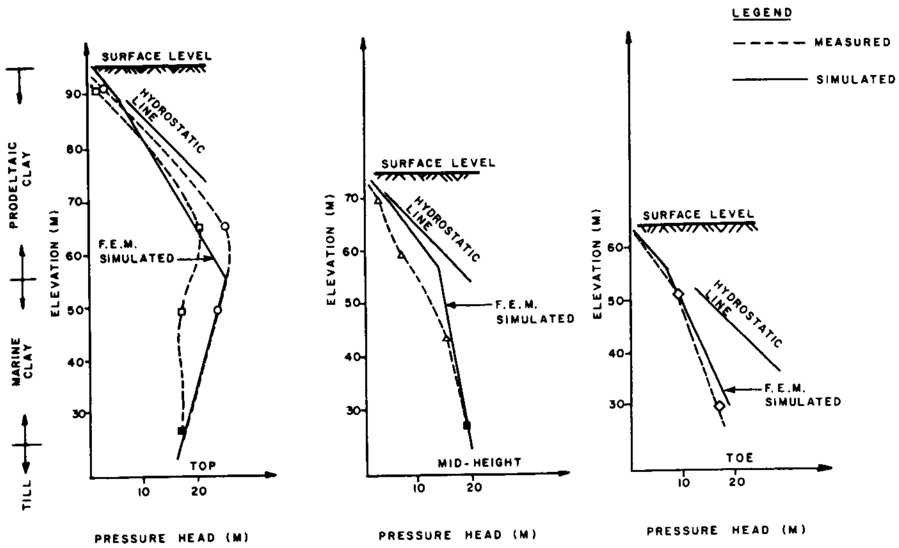


FIG. 7. Piezometric heads: Hull.

lower elevation, this stratum is responsible for the general downward gradient measured on this site. Similar findings have also been reported by Jarret and Eden (1970) for a site east of the City of Ottawa.

The flow net shown in Fig. 6 displays the generalized downward flow resulting from the small hydraulic head assumed and measured at two points in aquifer D. Piezometric measurements were made with Glötzl cells at different depths along four vertical axes; the comparison between the measured and the simulated distribution of pore pressures is shown in Fig. 7. In the superficial layer, the large permeability given to the crust created a flow parallel to the slope and the recording piezometers indicated that the water table fluctuated rather rapidly (1 m/week) and could approach the ground surface in every part of the slope.

Site No. 2—St-Urbain

This site is located along the Rivière-du-Gouffre, 100 km east of Quebec City, and this clay terrace, remnant of the Champlain Sea episode, lies along the sides of a narrow valley in the Precambrian Shield. Conditions are given in Fig. 8. The following three types of material have been identified.

A. *Grey silty marine clay:* Contains very thin discontinuous sand seams and traces of organic matter.

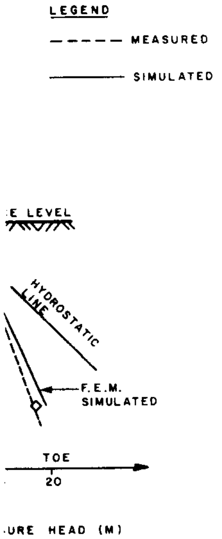
B. *Stratified clay and sand:* Below a certain level, deposit B consists of sand layers gradually thickening with depth. An important water seepage surface could be observed all year round along the river bank at that level.

C. *Till or fractured rock aquifer:* Ablation till covering the hillside is believed to extend under the marine clay deposit but if not so, the fractured bedrock constitutes an equivalent aquifer.

The resulting flow net is given in Fig. 8. Because no information on *in situ* permeability was available, especially with regard to anisotropy, assumptions had to be made so that the resulting flow net would conform with piezometer readings. Firstly, an absolute value of horizontal permeability and an anisotropy ratio $k_H/k_V = 100$ were assigned on the basis of grain size and the spacing of layers, and this large ratio was found to introduce a second phreatic surface at the interface of layers A and B. Because this was contradictory to the observation of steady seepage on the river bank face, a ratio of 10 was finally assumed so that calculated heads would conform with those measured at two vertical axes. At this site, Glötzl cells combined with open-tube piezometers indicated a strong downward gradient in the upper clay A, whereas the three piezometric tips in soil B gave a distribution approaching hydrostatic conditions.

Site No. 3—St-Ambroise

This site is contained in a narrow valley located approximately 70 km northeast of Montreal and bounded by bedrock slopes. In the middle of the 40 m clay deposit, a small river has cut a channel 20 m deep, the banks of which have been flattened by past landslides in the exceptionally sensitive clay. Typically, three types of soils have been identi[...]



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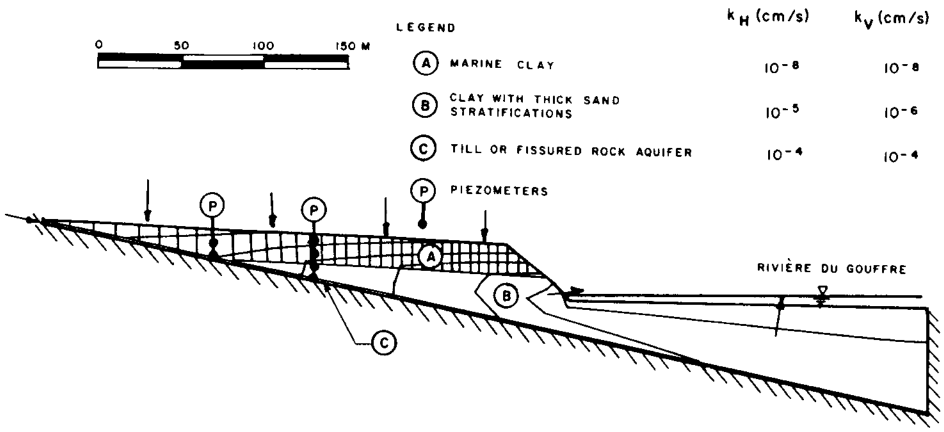


FIG. 8. Flow net: Saint-Urbain.

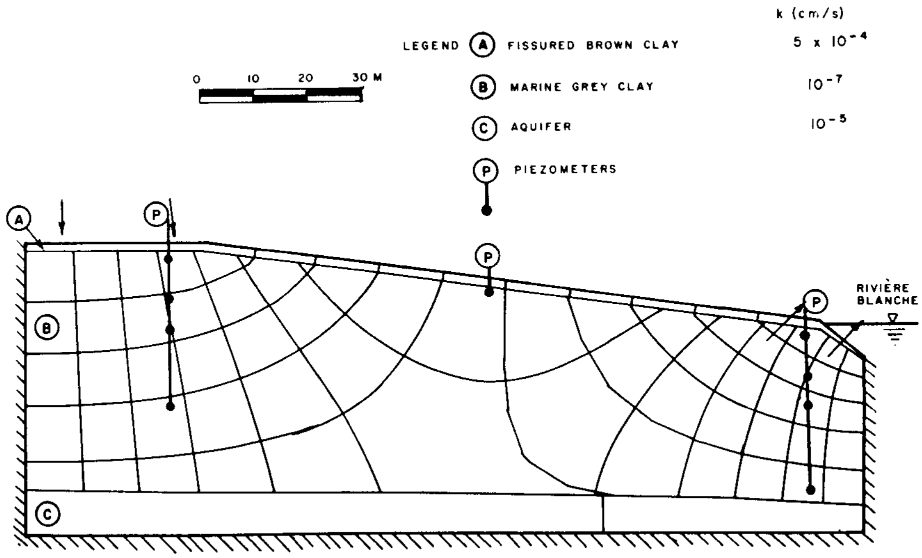


FIG. 9. Flow net: Saint-Ambroise.

A. *Desiccated clay crust:* Although the crust is less thick than at Hull, hydraulic conductivities of the order of k = 1–6 × 10^{-4} cm/s have been measured in this 2 m layer.

B. *Grey silty marine clay:* This clay is relatively homogeneous down to the 20 m depth and afterwards very thin sand seams have been observed. Hydraulic conductivities were measured through porous tips and were found to vary between k = 1 and 4 × 10^{-7} cm/s.

C. *Till:* This layer has been identified indirectly by auger-boring as gravelly and sandy material.

These conditions and piezometer locations are summarized in Fig. 9 where the resulting flow net is also given. Piezometric measurements have all been taken with open porous stone piezometers driven along two vertical axes at 9, 18, and 30 m depth. A the toe of the slope, where artesian conditions pre vailed, manometers were fitted to register the positiv pressures. Groundwater levels were measured at th 4 m depth by self-recording piezometers. Figure 1 gives the comparison between simulated and meas ured pore-pressure distributions. The results sho relatively small gradients, perhaps related to th geometry of the slope, and the impermeable bounc ary conditions inferred, which tend to confirm th noninfluence of recharge of the lower aquifer by th adjoining valley walls. On the other hand, measure ments support the idea that the water table come near the surface during periods of high infiltratio and lowers to the level of the intact grey clay durin the dry summer spells.

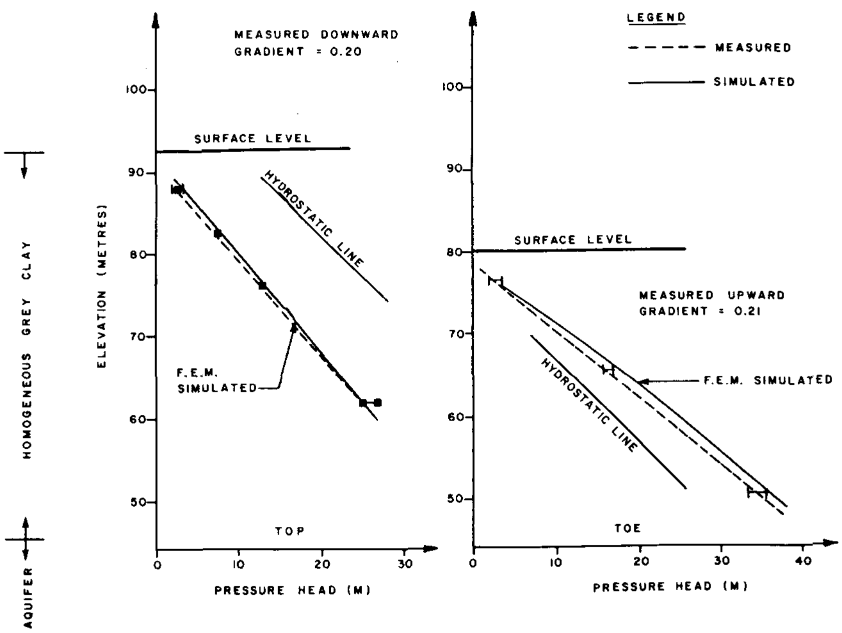


FIG. 10. Piezometric heads: St-Ambroise de Kildare.

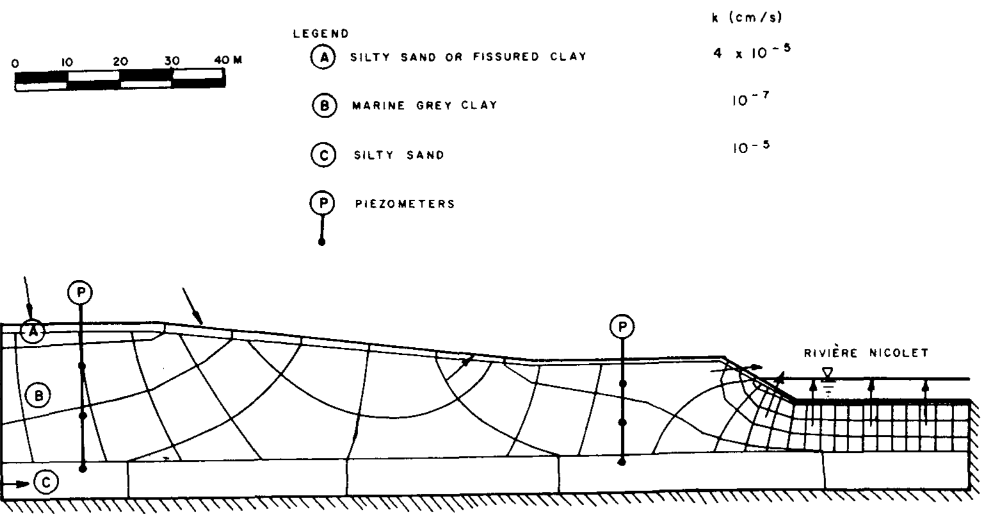


FIG. 11. Flow net: Nicolet.

Site No. 4—Nicolet

This site is located near the shore of Lac St-Pierre n a relatively level clay plateau cut only by the Nicolet river, creating an 18 m gentle slope except for he immediate river bank. The geometry and ground :onditions are given in Fig. 11 and the stratigraphy :an be described as follows.

A. *Compact silty sand:* Hydraulic conductivity ssumed to be $k = 4 \times 10^{-5}$ cm/s.

B. *Grey silty clay:* Hydraulic conductivity assumed o be 10^{-7} cm/s.

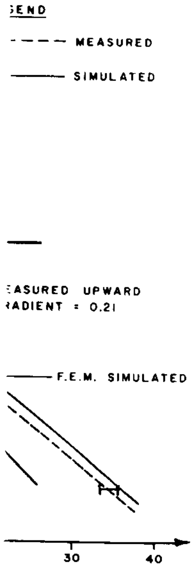
C. *Sandy and silty gravel:* Hydraulic conducti[...] assumed to be 10^{-5} cm/s. Although not confirm[...] the continuity of this deposit throughout the sect[...] has been assumed.

The main feature of the flow net shown in Fig[...] is the large upward gradient that can be anticipa[...] under the river, provided the C layer exists in t[...] location. Piezometers were of the Glötzl type [...] because of the great extent of the deposit, a sm[...] downward gradient at the top of the slope had to[...] assumed to conform with the piezometric readin[...] that location.

Discussion

With some limitations with re[...] distribution of piezometer tips, t[...] these tips, and the hydraulic co[...] ents, the present paper confirm[...] ons with regard to groundwat[...] uperficial permeable layer (wate[...] eriod of high infiltration rate a[...] e surface) and points out the [...] gional geology on pore-pressur[...] cinity of slopes made up of n[...] yers. The position of the low[...] resent in the Champlain Sea [...] he toe of the slope appears to co[...] f the upward hydraulic gradien[...] irectly influence the magnitu[...] tresses normal to the failure su[...] nfluence the shear strength of [...] oils. If the upward gradients exce[...] the vertical effective stresses bec[...] does the shear strength. On one [...] aquifer is confined and located b[...] slope, the magnitude of the u[...] inversely proportional to the v[...] tween the toe of the slope and th[...] and can substantially exceed th[...] On the other hand, if the aquifer [...] small hydraulic head, the clay de[...] a generalized downward gradien[...] increase in effective stresses an[...] increase in shear strength.

Permeability anisotropy is ack[...] puzzling factor, because it could [...] *in situ* by direct measurement an[...] study has shown its considerabl[...] flow regime. The absolute valu[...] varies exponentially with the ani[...] to a value of 25. The site at [...] stratified soil and the lack of [...] stratum precludes clear-cut result[...] t for r_k. With regard to the mar[...] he investigated sites, visual inspe[...] oes not support the assumpti[...] isotropy.



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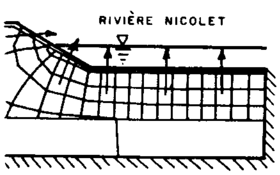
k (cm/s)

4 x 10^-5

10^-7

10^-5



v gravel: Hydraulic conducti
cm/s. Although not confirm
s deposit throughout the secti

of the flow net shown in Fig.
gradient that can be anticipa
vided the C layer exists in t
s were of the Glötzl type a
t extent of the deposit, a sm
at the top of the slope had to
with the piezometric reading

Discussion

With some limitations with regard to the spatial distribution of piezometer tips, the time of response of these tips, and the hydraulic conductivity measurements, the present paper confirms the usual assumptions with regard to groundwater behaviour in the superficial permeable layer (water level at surface in period of high infiltration rate and flow parallel to the surface) and points out the great influence of regional geology on pore-pressure distribution in the vicinity of slopes made up of massive marine clay layers. The position of the lower aquifer (always present in the Champlain Sea context) related to the toe of the slope appears to control the magnitude of the upward hydraulic gradients. These gradients directly influence the magnitude of the effective stresses normal to the failure surface and therefore influence the shear strength of these low-cohesion soils. If the upward gradients exceed the critical value, the vertical effective stresses become nearly zero, as does the shear strength. On one hand, if the lower aquifer is confined and located below the toe of the slope, the magnitude of the upward gradients is inversely proportional to the vertical distance between the toe of the slope and the top of the aquifer and can substantially exceed the critical gradients. On the other hand, if the aquifer is drained and has a small hydraulic head, the clay deposit is submitted to a generalized downward gradient, which implies an increase in effective stresses and consequently an increase in shear strength.

Permeability anisotropy is acknowledged to be a puzzling factor, because it could not be determined *in situ* by direct measurement and the finite-element study has shown its considerable influence on the flow regime. The absolute value of the gradients varies exponentially with the anisotropy ratio r_k up to a value of 25. The site at St-Urbain involved stratified soil and the lack of piezometers in this stratum precludes clear-cut results in the value to be set for r_k. With regard to the marine clay deposits of the investigated sites, visual inspection of the samples does not support the assumption of permeability anisotropy.

Conclusion

The aim of this study has been a better comprehension of the groundwater phenomena associated with the stability of natural slopes consisting primarily of soft sensitive Champlain Sea clays. It provides insight through a factor that is often subjective or indeterminate in stability analysis of these slopes in terms of effective stresses, namely, the pore-pressure distribution on the failure surface. It has been shown that with reasonable knowledge of the stratigraphy and of the boundary conditions (subdrainage or recharge by sloping bedrock) it is possible to draw a complete flow net from which the pore pressures can be adequately determined.

Acknowledgment

This research was financed by the Québec Ministry of Natural Resources and conducted at the Université de Sherbrooke.

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